# UNITED STATES
# NAVAL POSTGRADUATE SCHOOL

# THESIS

NAVY RESEARCH AND DEVELOPMENT

PROGRAM MANAGEMENT

by

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[redacted]

# NAVY RESEARCH AND DEVELOPMENT PROGRAM MANAGEMENT

by

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## ABSTRACT

Many management techniques have been discussed for application to various segments of the research and development process. All segments are analyzed to identify common problems and develop a consistent set of techniques to facilitate Navy program management. A selection model, program display, revised reporting techniques, and post-operational analysis are among the major topics discussed.

NAVY RESEARCH AND DEVELOPMENT
PROGRAM MANAGEMENT

ERRATA SHEET

1. Page 19, line 15: "vesting" vice "besting".

2. Page 20: should be printed to read "from the right" vice "from the left".

3. Page 31, title: "RESEARCH" vice "RESEACH".

4. Page 56, lines 8 & 9: hyphenate "prod-uct" vice "pro-duct".

5. Page 65, line 15: "theory" vice "thory".

6. Page 75, line 17: "to helping" vice "tohelping".

7. Page 76, line 6: "quandary" vice "quandry".

8. Page 77, box #1: "commitments" vice "committments".

9. Page 84, lines 10 & 11: hyphenate "propos-als" vice "propo-sals".

10. Page 89, line 7: "evaluation of" vice "evaluationof".

11. Page 96, lines 10 & 11: "propos-als" vice "propo-sals".

12. Page 98, bottom line: "approach if" vice "approach is".

13. Page 99, 5th line from bottom: "transfer" vice "trasnfer".

14. Page 99, 2nd & 3rd lines from bottom: "system-atic" vice "syste-matic".

15. Page 104, line 8: "to the" vice "tothe".

16. Page 104, lines 8 & 9: hyphenate "activ-ities" vice "acti-vities".

17. Page 115, lines 13 & 14: hyphenate "technolog-ical" vice "technolo-gical".

18. Page 127, lines 11 & 12: hyphenate "methodol-ogy" vice "methodo-logy".

19. Page 130, line 6: "affect" vice "effect".

20. Page 132, line 7: "help avoid" vice "help award".

21. Page 139, 2nd line from bottom: "affected" vice "effected".

22. Page 144, 5th line from bottom: "affect" vice "effect".

23. Page 150, lines 12 & 13: hyphenate "proj-ects" vice "pro-jects".

24. Page 151, lines 7 & 8: "proj-ects" vice "pro-jects".

25. Page 154, stem $Z_z$: delete one "is" in "... development is is ... ".

26. Page 162, lines 8 & 9: "proj-ects" vice "pro-jects".

27. Page 162, 5th & 6th lines from bottom: delete the first "s" in "pers-sonnel".

28. Page 172, line 1: "affected" vice "effected".

29. Page 176, lines 12 & 13: "proj-ects" vice "pro-jects".

30. Page 178, lines 8 & 9: "prob-ability" vice "pro-bability".

31. Page 192, lines 9 & 10: "extrap-olation" vice "extra-polation".

32. Page 196, line 14: "ultimately" vice "ultimate".

33. Page 202, line 9: "figure" vice "fugure".

34. Page 219, 7th & 8th lines from bottom: hyphenate "extrap-olation" vice "extra-polation".

35. Page 222, item 5(b), line 3: "flexible" vice "flexibile".

36. Page 222, item 8, line 1: "proj-ects" vice "pro-jects".

37. Page 241, item 10: "This document is subject to special export controls and each transmittal to foreign government or foreign nationals may be made only with prior approval of the U. S. Naval Postgraduate School." vice "Unlimited distribution".

# TABLE OF CONTENTS

CHAPTER PAGE

LIST OF FIGURES

| FIGURE | | PAGE |
|---|---|---|

## LIST OF ABBREVIATIONS

| | |
|---|---|
| AAW | Anti-war Warfare |
| ACNO | Assistant Chief of Naval Operations |
| ADO | Advanced Development Objective |
| ARMNET | Availability, Reliability, Maintainability Network Evaluation Techniques |
| ARPA | Advanced Research Projects Agency |
| ASN(R&D) | Assistant Secretary of the Navy (R&D) |
| ASW | Anti-submarine Warfare |
| BUDOCKS | Bureau of Yards and Docks |
| BUMED | Bureau of Medicine and Surgery |
| BUPERS | Bureau of Personnel |
| BUSANDA | Bureau of Supplies and Accounts |
| BUSHIPS | Bureau of Ships |
| BUWEPS | Bureau of Naval Weapons |
| CD | Contract Definition |
| CF | Contract Formulation |
| CIRCUS | Cost Information Retrieval and Characteristics Utilization System |
| CMC | Commandant of the Marine Corps |
| CND | Chief of Naval Development |
| CNM | Chief of Naval Material |
| CNO | Chief of Naval Operations |
| CNP | Chief of Naval Personnel |
| CNR | Chief of Naval Research |
| DCNM(D) | Deputy Chief of Naval Material (Development) |
| DCNO(D) | Deputy Chief of Naval Operations (Development) |
| DDR&E | Director of Defense Research and Engineering |
| DESM | Development Evaluation and Specification Modification System |
| DNL | Director of Naval Laboratories |
| DoD | Department of Defense |
| EDG | Exploratory Development Goals |
| FBM | Fleet Ballistic Missile |
| FYDP | Five-Year Defense Program |
| GOR | General Operational Requirements |
| INS | Institute of Naval Studies |
| JCS | Joint Chiefs of Staff |
| JLRSS | Joint Long-Range Strategic Study |
| JSCP | Joint Strategic Capabilities Plan |
| JSOP | Joint Strategic Objectives Plan |
| MRO | Navy Mid-Range Objectives |
| NARDIS | Navy Automated Research and Development Information System |
| NCP | Navy Capabilities Plan |

| | |
|---|---|
| NLRSS | Navy Long-Range Strategic Study |
| NMS | Navy Mid-Range Study |
| NMSE | Naval Material and Support Establishment |
| NRO | Naval Research Objectives |
| NSP | Navy Support Plan |
| OEG | Operations Evaluation Group |
| ONM | Offfice of Naval Material |
| ONR | Office of Naval Research |
| OPA | Office of Program Appraisal |
| OSD | Office of the Secretary of Defense |
| PCR | Program Change Request |
| PERT | Program Evaluation and Review Technique |
| PO | Navy Program Objectives |
| PTA | Proposed Technical Approach |
| R&D | Research and Development |
| RDT&E | Research, Development, Test, and Evaluation |
| RFP | Request for Proposal |
| SECDEF | Secretary of Defense |
| SECNAV | Secretary of the Navy |
| SOR | Specific Operational Requirements |
| TDP | Technical Development Plan |
| TSOR | Tentative Specific Operational Requirements |
| VCNM | Vice Chief of Naval Material |
| VCNO | Vice Chief of Naval Operations |
| VECP | Value Engineering Change Proposals |
| WSEG | Weapons Systems Evaluation Group |

ACKNOWLEDGEMENTS

I would like to express my appreciation for the academic freedom permitted in topic selection by the Operations Analysis Department Chairman and Curricular Officers. The chosen topic, Navy Research and Development Program Management, is a broad and complex subject. Studying it proved challenging and rewarding. Most of the published literature on the subject is wisely restricted to specific problems within this area. I feel that the attempt to consider the parts together has emphasized some very interesting aspects of the problem and cast serious doubts on the applicability of some proposed solutions to the component problems.

I am especially indebted to my advisor, Professor Arthur Carol. His great patience and endurance in bearing with me to the end of this "book" are greatly appreciated. His well-timed encouragement and restraint and his frequent discussions of the "grey areas" have contributed greatly to the final product. I accept full responsibility for any remaining errors.

I would also like to express my appreciation to Professor Jerry Dake for reading and making very helpful comments on the rough draft.

Navy Research and Development Program Management

Introduction.

> In our laboratory we have an Assistant Director in charge of reading all articles that tell us how to run our own business--and writing letters to management explaining why most of them do not apply. [1]

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Special Notice.

This notice is designed to save time for some readers. The thesis is directed to two groups of people: those experienced in management of R&D activities, and those just beginning their R&D duties. For the former, the last section of Chapter 8 (Post-Operational Analysis), Chapter 9 (Summary), and Chapter 10 (Conclusions), contain information of interest. The other chapters describe and analyze the R&D process and develop the lines of reasoning from which the conclusions were derived.

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Research and development articles typically begin with an impressive array of statistics to justify the need for the topic study. R&D is big business($7 billion big in the Department of Defense in 1966)[2]; it is

[1] B-60, pp 121.

[2] B-28, pp 1.

growing rapidly (R&D expenditures by DoD in 1961 were about $4 billion[3]). More detailed statistics are included in Appendix A but the statistics by themselves don't tell the whole story. They serve as a common line of departure for systems analysts, psychologists, social scientists, educators, consultants, and managers for study of the many aspects of the R&D process. The spectrum of approaches and proposals are brought together here to identify common problems and establish consistent solutions.

The purpose here is not to replace managers, but rather to seek procedures that will be useful to managers in controlling and reducing the amount of uncertainty in decision-making and in paving the way toward more precise and accurate planning. It is necessary to go beyond the rejection technique used by the Assistant Director mentioned in the opening quotation to the task of assembling a consistent set of techniques to increase the efficiency and effectiveness of R&D management.

The degree of skill in planning and controlling the research and development process and the rate at which that skill is acquired constitute a major positive control over future events--both in improving national standards and in maintaining an internationally competitive posture. The planning of research and development is therefore a vital factor in the overall planning process, and it is the foundation of capital investment policy.

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[3] B-62, pp 4.

The growth of R&D has brought the assertion that diminishing returns have set in on R&D investments so that those investments are coming into equilibrium with alternative investments;[4] i.e., the current proportion of funds devoted to R&D is approaching the "best" proportion. This is a very difficult situation to analyze, since the purpose of R&D is to upset the equilibrium, and since the actual returns on research are usually difficult to measure. Hence it is not surprising to find disagreement on whether returns on alternative investments have been equalized. But it does appear that a "profit squeeze" of sorts is occurring, and the increased R&D efforts are yielding more and more proposals. These conditions necessitate greater care and improved techniques in project selection and control, and in measuring and controlling progress in R&D.

The emphasis on the need for better techniques for managing, measuring, and controlling R&D does not mean that these areas are being neglected; such study is in progress, and many proposals have been successfully introduced. An example of the importance attached to this area by the Department of Defense is the position of the Director of Defense Research and Engineering (DDR&E) as the most senior of the assistants to the Secretary of Defense. In the Navy, the Assistant Secretary (Research and Development)(ASN(R&D)), has the unusual (and useful) authority for administering the Navy's RDT&E fund allocation.

[4] A-18, pp 75.

The problem is not one of oversight, but simply one of a need for continuing improvements.

A more direct reason for concern with the management of R&D is the government's heavy and growing emphasis on cost-effectiveness techniques and considerations in general, and their applications to the planning-programming-budgeting process in particular. While past research and development efforts have yielded many outstanding achievements, many items were developed at costs three to ten times larger than estimates; large errors in prediction of completion time, reliability, and effectiveness are also common. All disrupt the planning, and frequently force discontinuities on projects which don't promise immediate returns. The Resource Management Systems effort and Project PRIME[5] can be expected to cast harsh light upon R&D planning. In these days of long lead times, forewarned may not be fore-armed, but a little homework may be helpful.

Briefly the major phases of R&D program formulation considered in the following chapters are:

(1) Establish well-defined objectives at all levels of the organization.
(2) Evaluate current and anticipated threats, commitments, and capabilities.
(3) Develop a scenario.
(4) Formulate plans and policies.
(5) Search for potential projects.
(6) Evaluate military value of projects.
(7) Estimate project characteristics such as cost, reliability, and time required for completion, and trade offs among these characteristics.

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[5] See reference B-17.

(8) Select projects to be included in the program.
(9) Review program for balance.
(10) Establish administrative and funding flexibility.
(11) Establish effective feedback on analytical procedures employed throughout the program.

These phases are ripe with uncertainties, and communications and organizational difficulties.

The reasons for studying R&D management are summarized as follows:

(1) R&D is a large and growing task.
(2) R&D efforts exert a profound influence on future strength and well-being of the nation.
(3) There are no widely accepted procedures for conducting an optimal R&D program, and most of the literature deals with isolated portions of the program.
(4) Rapid growth of R&D expenditures and governmental interest in cost effectiveness combine to require the study.

The study here is applied to the Navy RDT&E program, but the observations, results and conclusions are considered to be more generally applicable.

The presentation begins with a condensed description of the Navy RDT&E organization, emphasizing the handling of the planning-programming-budgeting process. The second chapter discusses the dominant role played by uncertainty in research and development, and the resulting communications and organizational difficulties. Chapter 3 discusses the initial planning procedures and project genesis. The sequential evaluation of proposed R&D projects is the subject of Chapter 4. The fifth chapter develops criteria for project selection and presents a model to assist the manager in the selection process. Chapter 6 proposes a display to assist in program control and provide

information on the model constraints; additional control considerations are presented in Chapter 7. Development of a data bank and post-operational analysis are discussed in Chapter 8. Procedures are summarized in Chapter 9 and conclusions are presented in Chapter 10.

## Chapter 1. Research, Development, Test and Evaluation (RDT&E) and the Navy Organization

> The Navy was organized with a peculiar psychology which "...frequently seemed to retire from the realm of logic into a dim world in which Neptune was god, Mahan his prophet, and the U. S Navy the only true church."[6]
>
> H. L. Stimson

Much has transpired within the Navy in recent years which refutes the opening quotation. Significant steps have been taken away from the traditional bilinear structure toward a unilinear structure in which responsibility and authority may be clearly assigned. Most notable is the re-organization of 1 May 1966, which placed the Chief of Naval Material under the Chief of Naval Operations. The planning-programming-budgeting process instituted by the Department of Defense (DoD) has had far-reaching organizational effects. The handling of research and development in the Navy is well spelled-out by the Navy RDT&E Management Guide,[7] a publication whose major shortcoming is that apparently not enough people are aware of it.

This chapter presents a brief factual description of the Navy offices and units having primary responsibilities in RDT&E management. The organization charts stress RDT&E functions. Emphasis is placed on activity interrelationships, the planning-programming-budgeting process, the procedures for taking an R&D proposal from

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[6] B-62 , pp 61-62.

[7] B-18. This publication and Navy and DoD Instructions are the primary sources of information for this chapter.

its fuzzy beginnings to its conclusion as an operable system or component, and the reporting procedures used in monitoring and controlling the RDT&E effort. The systems analysis, operations analysis, and management techniques of subsequent chapters will refer to the organization described here.

One limitation on this chapter is its dependence on instructions and other formal guides. Informal meetings, telephone conversations, and memos, which may actually play a major part in the organization's operation, are generally omitted. The documents which prescribe the formal structure in fact encourage informal communications and cooperation; comments to the effect that "nothing in this instruction shall be construed so as to restrict cooperation between parties" are common.

The RDT&E effort is accounted for under the sixth of nine DoD programs. It is divided into 6 funding categories which the Navy uses in assigning responsibility and authority and which will be useful in the discussion of the Navy R&D organization.

Program 6--Research and Development[8]

1. Research--study to extend the frontiers of knowledge
2. Exploratory Development-seek new applications of science and technology
3. Advanced Development--more detailed exploration of area of high potential requiring further investigation to reduce the risk involved in large scale development expenditures.
4. Engineering Development--unit and component hardware development

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[8] B-30 , pp IV-2-106.

5. Management and Support
6. Operational Systems Development--generally a large project involving a combination of many components and scientific disciplines for a specified purpose; already approved for procurement and employment.

The descriptions give a general indication of the type of work involved in each category. There is really a spectrum of R&D activity corresponding to the uncertainty of the outcome, and the boundaries of the categories are not well-defined. With the exception of the Research category, all elements of the Navy program are oreinted toward a specific mission in a particular environment.[9]

Organization Structure and Responsibilities of Major RDT&E Components.

One of the major purposes of the creation of the Department of Defense (DoD) was "to eliminate unnecessary duplication. . . particularly in the field of research and engineering by besting its overall direction and control in the Secretary of Defense."[10] The DoD organization is presented in Figure 1-1. The Director of Defense Research and Engineering (DDR&E) ranks ahead of all other Assistant Secretaries of Defense, and his deputy is a full Assistant Secretary. DDR&E has the authority to approve, modify, or disapprove programs and projects of the military departments and other DoD agencies, and to eliminate unpromising or unnecessarily duplicative programs and initiate or

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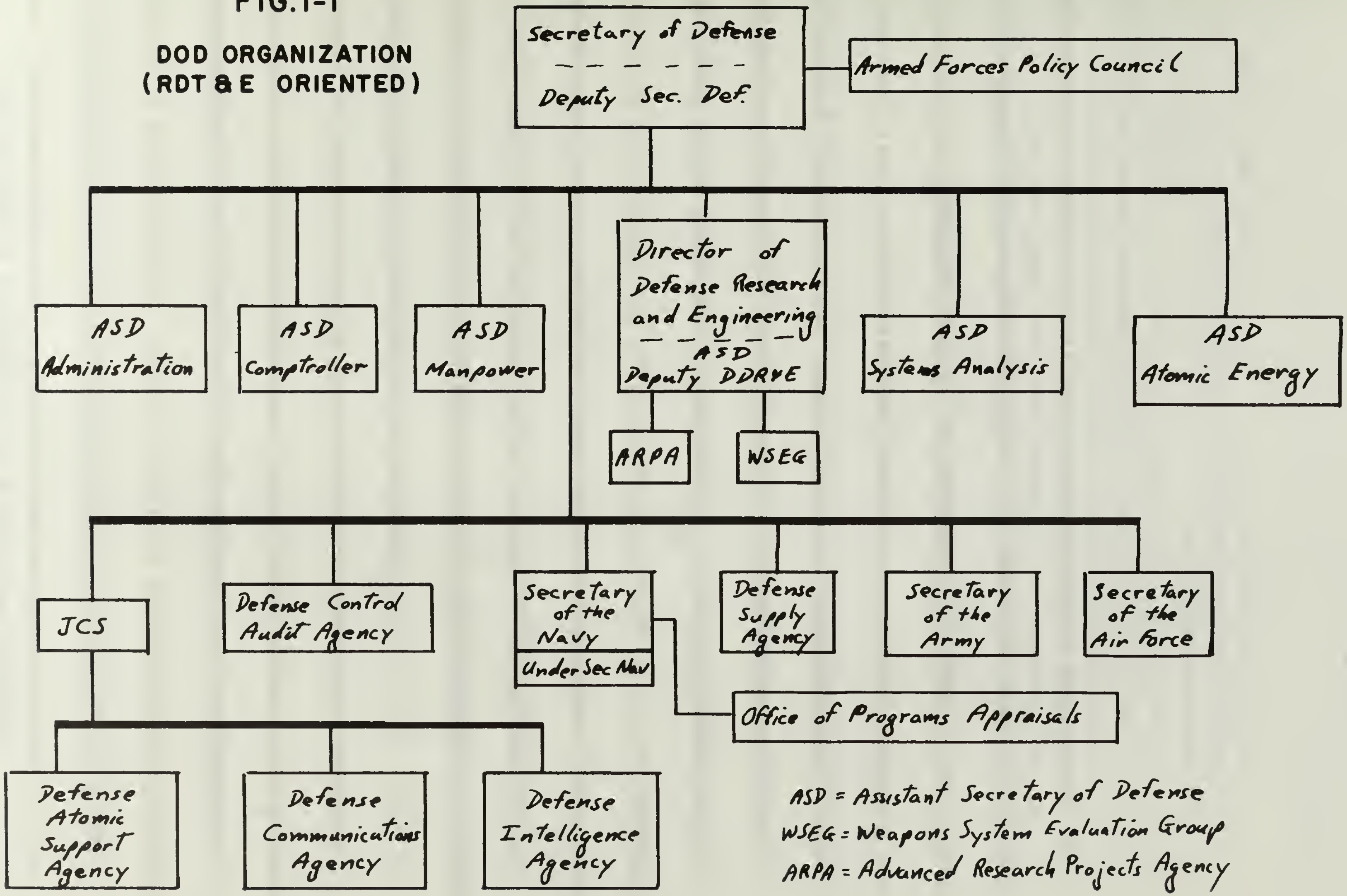
[9] C-4, pp 2.

[10] B-63[illegible], pp 136-7.

FIG. I-1

DOD ORGANIZATION
(RDT&E ORIENTED)



support promising ones. The Joint Chiefs of Staff (JCS) have an advisory role in research and development activities.[11]

The Assistant Secretary of the Navy (Research and Development) (ASN(R&D)) exercises responsibility for Department-wide policy guidance and supervision of all research, development, engineering, test, and evaluation efforts within the Navy, and manages the congressional appropriation category "Research, Development, Test, and Evaluation, Navy." He has only a small staff of technical assistants and is supported and assisted primarily by the Deputy Chief of Naval Operations (Development) (DCNO(D)), the Deputy Chief of Staff (R&D) Marine Corps, the Chief of Naval Development (CND) who is also the Deputy Chief of Naval Material (Development)(DCNM(D)), the Chief of Naval Research (CNR), and the Project Managers of the SECNAV Designated Projects. ASN(R&D) also provides direct supervision of the Office of Naval Research.[12]

The Chief of Naval Operations (CNO), assisted in his R&D responsibilities by DCNO(D), utilizes technological projections in making long- and mid-range plans, and maintains a 10-year research and development program to ensure a balanced effort consistent with

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[11] B-18, pp 1-2. Pages of the Navy RDT&E Manual are designated by chapter number or Appendix letter, a hyphen, and page number of that chapter or appendix. The reference "pp 1-2" refers to Chapter 1, page 2.

[12] C-31, pp 1, 2; B-18, pp 1-4.

future plans. DCNO(D) is charged with coordinating the Navy Advanced Development, Engineering Development and Operational Systems Development programs and immediate requirements. CNO is charged with the formidable task of appraising the potential military worth of the 10-year R&D program with respect to its cost, revising the program to obtain the optimum return on the R&D investment, and making appropriate recommendations to ASN(R&D). CNO gives the final go-ahead on major development projects by approving the Technical Development Plans (TDP), and after reviewing the results of a completed R&D project may, with concurrence of CNM, make recommendations to SECNAV for production. The organization of the office of DCNO(D) is presented in Figure 1-3. The Commandant of the Marine Corps (CMC) performs similar duties for the Marine Corps.[13] Figure 1-2 presents the Navy top management structure.

The Chief of Naval Material provides direction and management coordination of the RDT&E Program of the Navy Material Support Establishment (NMSE) in response to CNO/CMC requirements by consolidating the approved RDT&E projects plans from the material bureaus. CNM consults with the Chief of Naval Personnel (CNP) on all personnel requirements, including training, for support of NMSE developments expected to be introduced into the fleet. CNM appraises the cost and effectiveness of the NMSE RDT&E Program, advises CNO of significant deviation from plans, and may recommend

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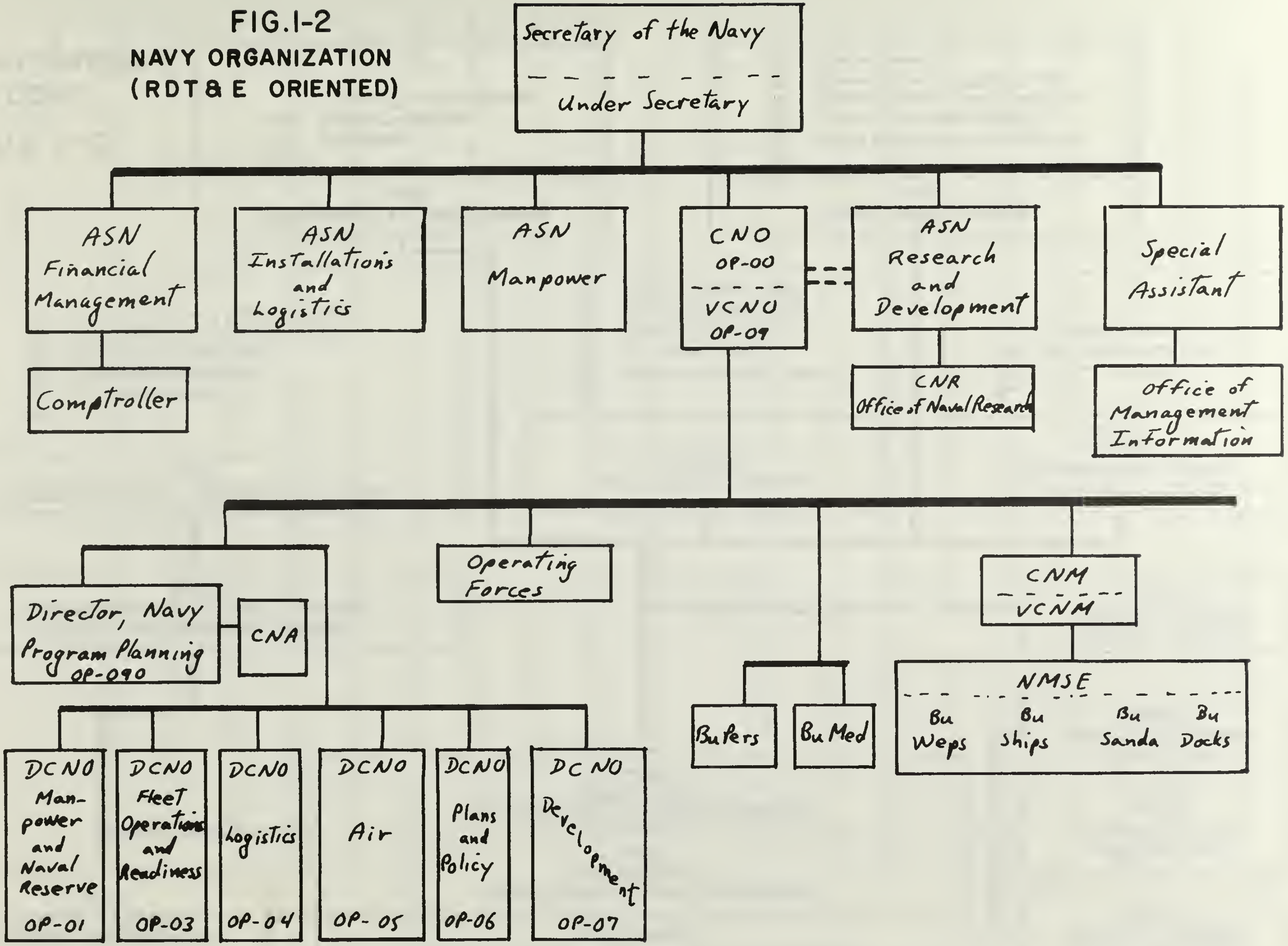
[13] C-31, pp 3-6.

FIG.I-2

NAVY ORGANIZATION

(RDT&E ORIENTED)



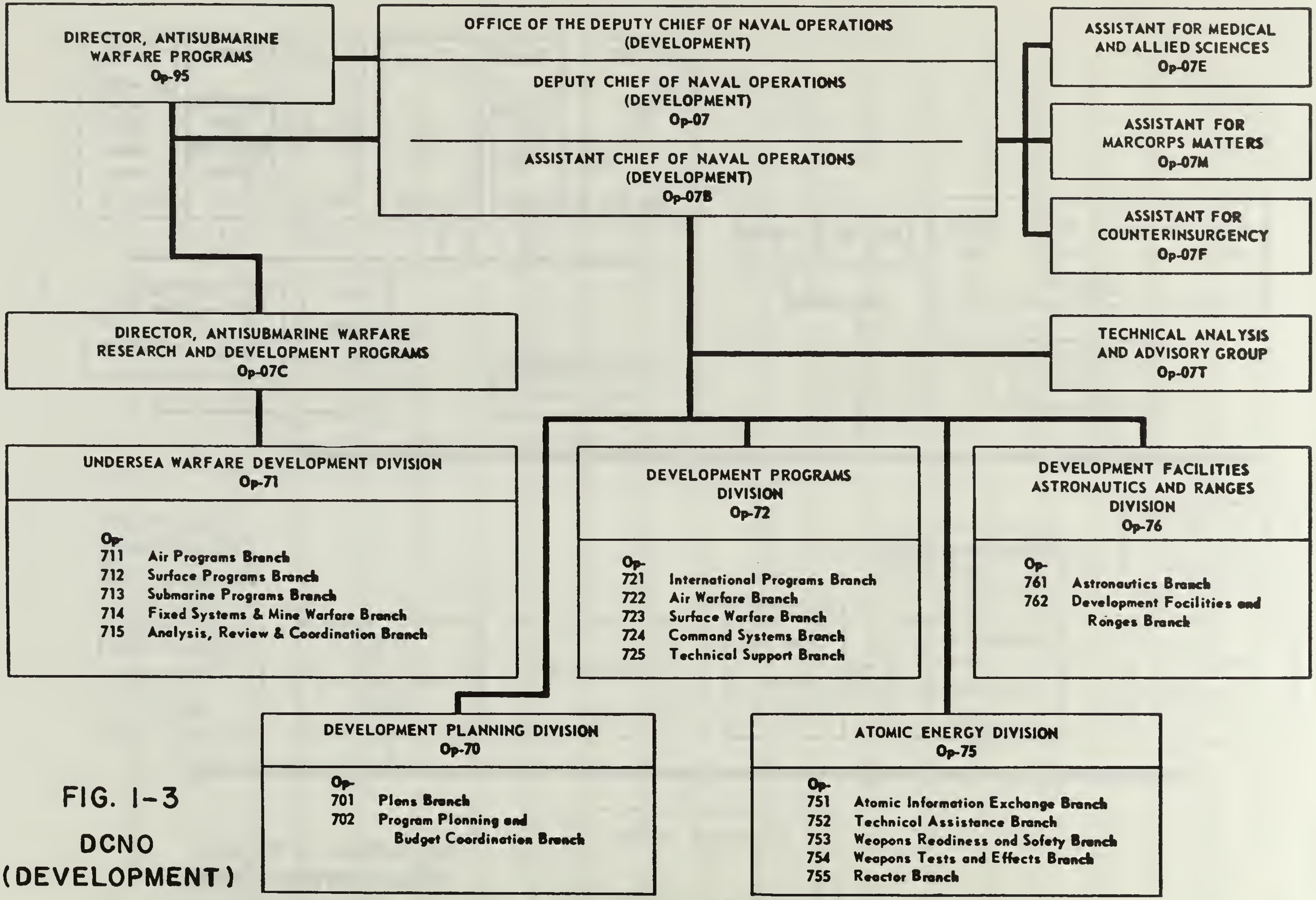



FIG. 1-3
DCNO
(DEVELOPMENT)

reconsideration of operational requirements when necessary. He also provides technical and fiscal inputs to other Navy studies.[14]

The Chief of Naval Development (CND/DCNM(D)) (see Figure 1-4 for organization chart) coordinates the Navy's Exploratory Development Program for ASN(R&D), operating closely with CNR, CNP, and Chief, BUMED. CND promulgates Exploratory Development Goals (EDG), and reviews and coordinates proposals from the NMSE, CMC, CNP, CNR, and Chief, BUMED. He appraises the overall program balance and may recommend changes in funding to ASN(R&D). CND makes an annual appraisal of opportunities afforded by the Exploratory Development program for increased naval warfare capabilities.[15]

The Chief of Naval Research (CNR) heads the Office of Naval Research (ONR) and is responsible for the conduct of basic and applied research in augmentation of and in conjunction with the research and development conducted by all other activities in the Navy. He may also conduct Exploratory Development in collaboration with developing agencies to assist in the orderly transition from research to development. CNR coordinates Navy participation in joint service scientific studies and related Navy studies. ONR assumes financial responsibility for research projects, but may share portions of this responsibility with the various bureaus and

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[14] C-31, pp 6-8.

[15] Ibid., pp 8-9; B-65, pp E-24.

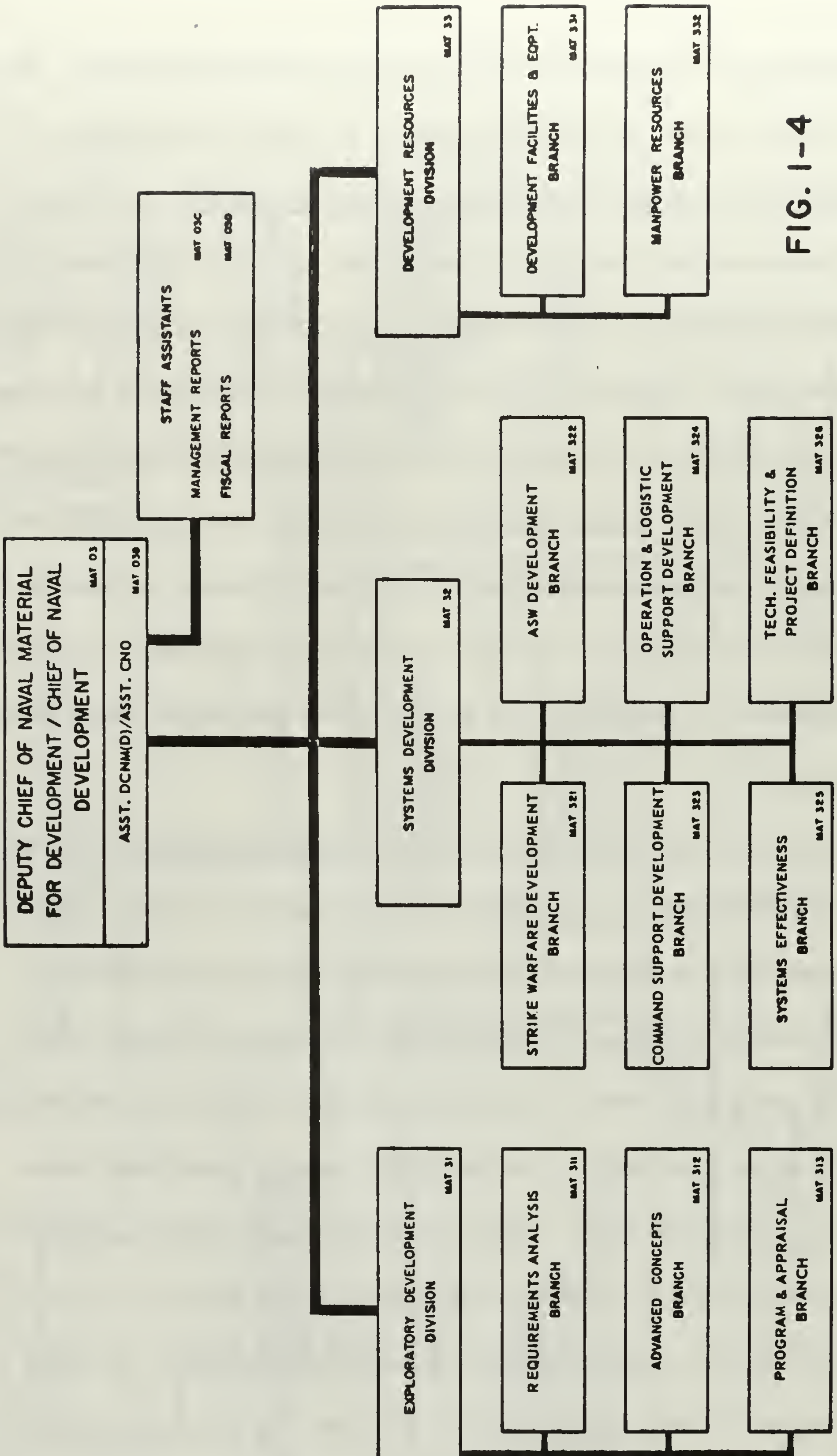
DEPUTY CHIEF OF NAVAL MATERIAL FOR DEVELOPMENT / CHIEF OF NAVAL DEVELOPMENT
MAT 03
ASST. DCNM(D)/ASST. CNO
MAT 03B
STAFF ASSISTANTS
MANAGEMENT REPORTS MAT 03C
FISCAL REPORTS MAT 03D
EXPLORATORY DEVELOPMENT DIVISION
MAT 31
REQUIREMENTS ANALYSIS BRANCH
MAT 311
ADVANCED CONCEPTS BRANCH
MAT 312
PROGRAM & APPRAISAL BRANCH
MAT 313
SYSTEMS DEVELOPMENT DIVISION
MAT 32
STRIKE WARFARE DEVELOPMENT BRANCH
MAT 321
ASW DEVELOPMENT BRANCH
MAT 322
COMMAND SUPPORT DEVELOPMENT BRANCH
MAT 323
OPERATION & LOGISTIC SUPPORT DEVELOPMENT BRANCH
MAT 324
SYSTEMS EFFECTIVENESS BRANCH
MAT 325
TECH. FEASIBILITY & PROJECT DEFINITION BRANCH
MAT 326
DEVELOPMENT RESOURCES DIVISION
MAT 33
DEVELOPMENT FACILITIES & EQPT. BRANCH
MAT 331
MANPOWER RESOURCES BRANCH
MAT 332

FIG. 1-4

offices of the Department of the Navy in proportion to their interest. CNR is charged with a large share of the Navy's responsibility for keeping current with scientific developments and trends on a world-wide basis, and with modifying the direction of the Navy's research accordingly. Most of ASN(R&D)'s support in managing the RDT&E appropriations is supplied by CNR. CNR provides advice to ASN(R&D) on research in general and on any modification of the Department of the Navy's in-house capacity to perform research or development, including government-owned contractor-operated facilities. All research contracts with educational and non-profit institutions are controlled by ONR, as are all Navy functions involving patents, inventions, and copyrights. The ONR organization is depicted in Figure 1-5. The Navy's laboratories--some 50 of them with an annual workload amounting to about $550 million, or about 30% of the annual Navy RDT&E budget--are not under ONR control, but report to the Director of Naval Laboratories (DNL), a civilian coequal with CNR and CND.[16]

Project Managers are assigned to Secretary of the Navy designated projects to lead a highly centralized attack on a single high priority problem or system development. They act under the guidance and delegated authority of CNM to exercise technical, financial, and administrative control over personnel, material, contractors, and

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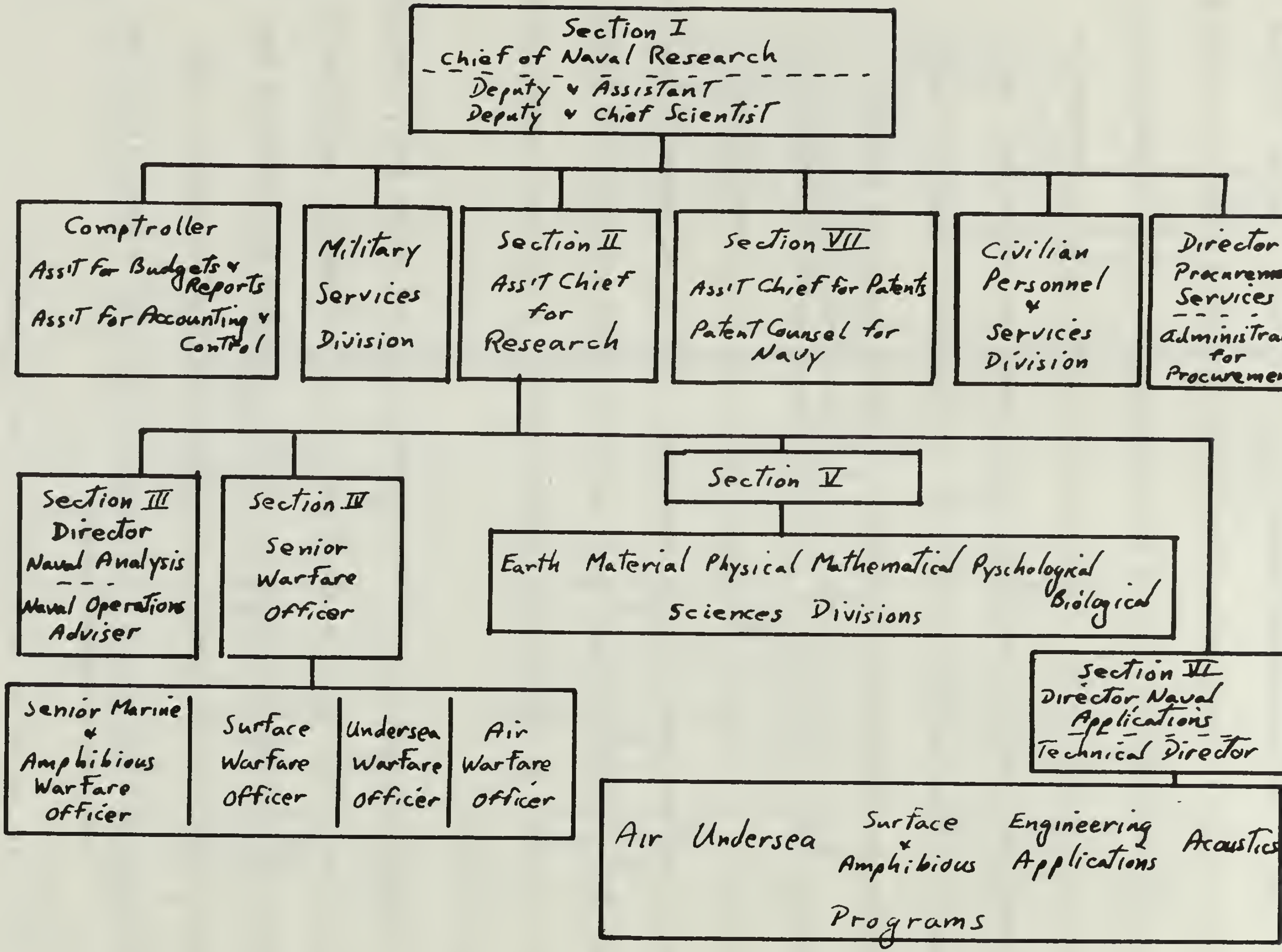
[16] C-31, pp 10-12; B-18, pp 1-7 and Appendix F.

FIG. 1-5

OFFICE OF NAVAL RESEARCH



all other resources required for the project. Support is generally supplied by BuWeps or BuShips within the NMSE.[17]

Primary cost-effectiveness responsibilities are vested with (1) the Navy Program Planning Office of the Office of CNO, whose director is Scientific Officer to the Center for Naval Analyses (CNA), where most of its quantitative work is carried out; (2) the Office of Program Appraisal, which provides a small staff capability to review program cost-effectiveness for the Secretary of the Navy; and (3) the Office of Naval Material (ONM), which presents technical and economic data to CNM on requirement feasibility.[18]

There are many other R&D activities in the Navy which perform important duties, but the preceding discussion is representative of the top R&D management. The R&D function may be traced from these offices to various levels of the organization. Examples of the R&D function in the Bureau of Naval Weapons and the Bureau of Ships are shown in Figures 1-6 and 1-7 respectively. For a more detailed presentation than given here, the reader is referred to the Navy RDT&E Management Guide (B-18).

Numerous committees are formed to support the R&D effort. Some important examples are:

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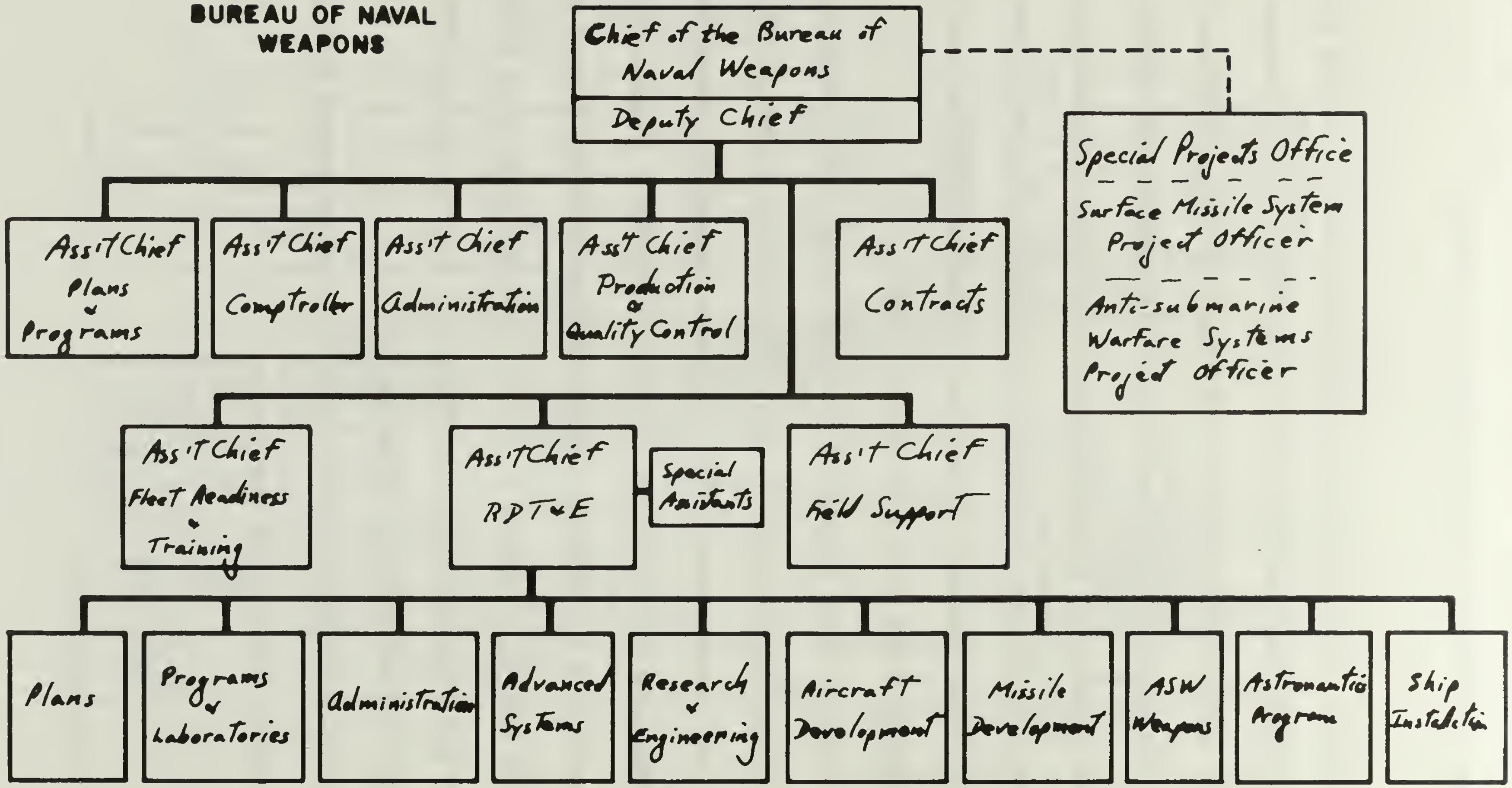
[17] C-31, pp 13-14.

[18] B-18, pp 3-10.

FIG. I-6

BUREAU OF NAVAL WEAPONS



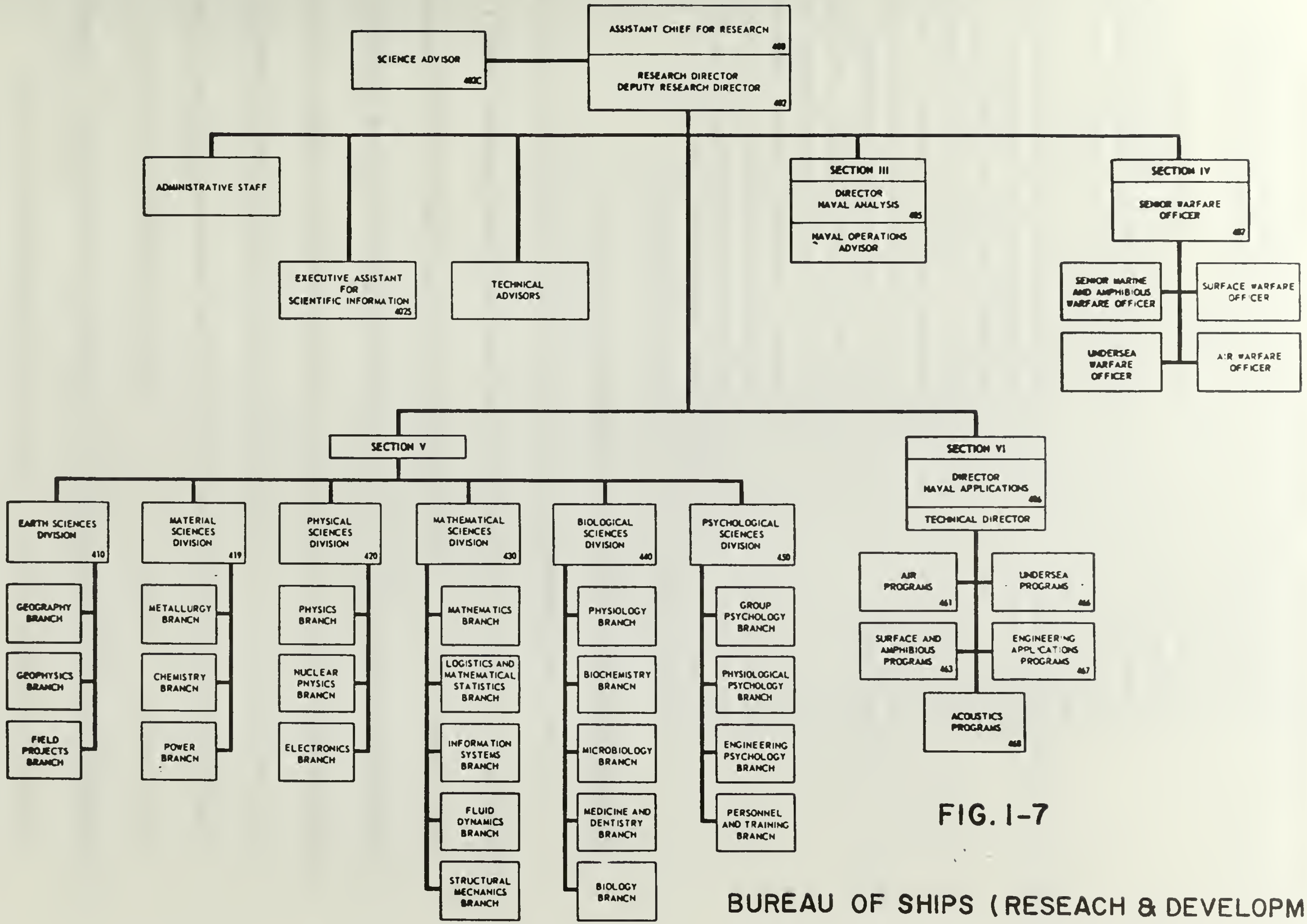



FIG. I-7

BUREAU OF SHIPS (RESEACH & DEVELOPMENT)

(1) Navy Research and Development Committee--consists of top Navy RDT&E management, operating on an informal "official family" basis, meeting weekly when ASN(R&D) is available; topics unrestricted.
(2) Naval Research Advisory Committee--consists of 15 civilians pre-eminent in science research and development; 4 meetings held annually, attended by Navy R&D top management; provide advice on general policy, research trends, and R&D administration.
(3) Navy Research and Development Review Board--considers R&D planning objectives, annual R&D plans, and R&D projects, and forwards the planning objectives and plans to CNO and ASN(R&D) for approval. DCNO(D) is the chairman, and members include high ranking representatives of the operating forces from OP-03 (DCNO(Fleet Operations and Readiness)). The board meets as directed by DCNO(D).
(4) Chief of Naval Operations Advisory Board (CAB)--provides advice and recommendations to CNO on Navy programs in general with respect to strategic concepts, plans, policies, and the budget. This is a top level review board for Naval Operations and is conducted by the Deputy Chief of Naval Operations, CNM, and others. Meetings are scheduled at the discretion of the Chairman, DCNO(D).[19]

Planning-Programming-and-Budgeting in the Navy

The top management of Navy RDT&E is concerned with long- and medium-range planning and with the year-to-year conduct of R&D. The planning-programming-budgeting process deals with the questions (1) What would we like to do? ; (2) What resources do we have available to do it with? ; and (3) What is the best that we can do with these limited resources? It compares plans and objectives with existing capabilities and facilities and with the Congressional appropriations. The planning considers strategic capability, defensive capability, trooplift and fighting capability for limited war, and other "outputs" or operating capabilities. Congressional appropriations have

[19] B-18, pp E-61-64.

traditionally been made in terms of defense system inputs, and probably will continue to be made that way. The principal subdivisions of the defense appropriation are:[20]

Title I: Military Personnel
Title II: Operation and Maintenance
Title III: Procurement
Title IV: Research, Development, Test and Evaluation (RDT&E)
Title V: Civil Defense
Title VI: General Provisions

The RDT&E appropriation, which conveniently corresponds directly to DoD's Program 6, is further divided into eight principal budget activities as follows:[21]

1. Military sciences
2. Aircraft and related equipment
3. Missiles and related equipment
4. Military astronautics and related equipment
5. Ships and small craft and related equipment
6. Ordnance, combat vehicles, and related equipment
7. Other equipment
8. Program-wide management and support

The obvious gaps between planning terms and budget classifications are to be bridged by the programming phase. The programming phase is also designed to assist in making a continuous appraisal of programs, in reporting progress, and in integrating the DoD information and planning systems.[22]

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[20] B-18, pp 4-3.

[21] Ibid. For a complete listing of numbered DoD Programs see Appendix B.

[22] Ibid., pp 3-1, 2.

The Five-Year Defense Program (FYDP)--formerly known as the Five-Year Force Structure and Financial Plan--is the summation of all approved programs from all DoD components and is the foundation of the Programming System. It may be represented as a three-dimensional matrix or graph, with programs (outputs) each broken down into resource requirements (inputs) on two of the axes, and the third axis represents expenditures over time. (See Figure 1-8.) The programs are further subdivided into program elements, such as the Fleet Ballistic Missile (FBM) System, VTOL aircraft, the EX-10 torpedo development, etc.

In classifying items in the DoD Programming System, the research and development program is to include all effort which has not been directly identified with other programs. Deciding when such identification has occurred is one of several delicate interfaces of the system; "identification" is typically interpreted as occurring when the decision is made to produce for inventory.

An unfortunate drawback of the FYDP for RDT&E activities is that it makes no provision for presently undefined but anticipated development programs. The result is that casual glance at a particular FYDP gives the impression that DoD intends to phase out R&D.[24] Since this would be a most improbable event, it is a deficiency in the FYDP's ability to predict and plan future expenditures. It is not likely that the nature of R&D will permit prediction and description of projects to be started in 3, 4, or 5 years in the detail required for DoD approval.

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[22] B-18, pp 3-1, 2.

[24] B-18, pp 3-10.

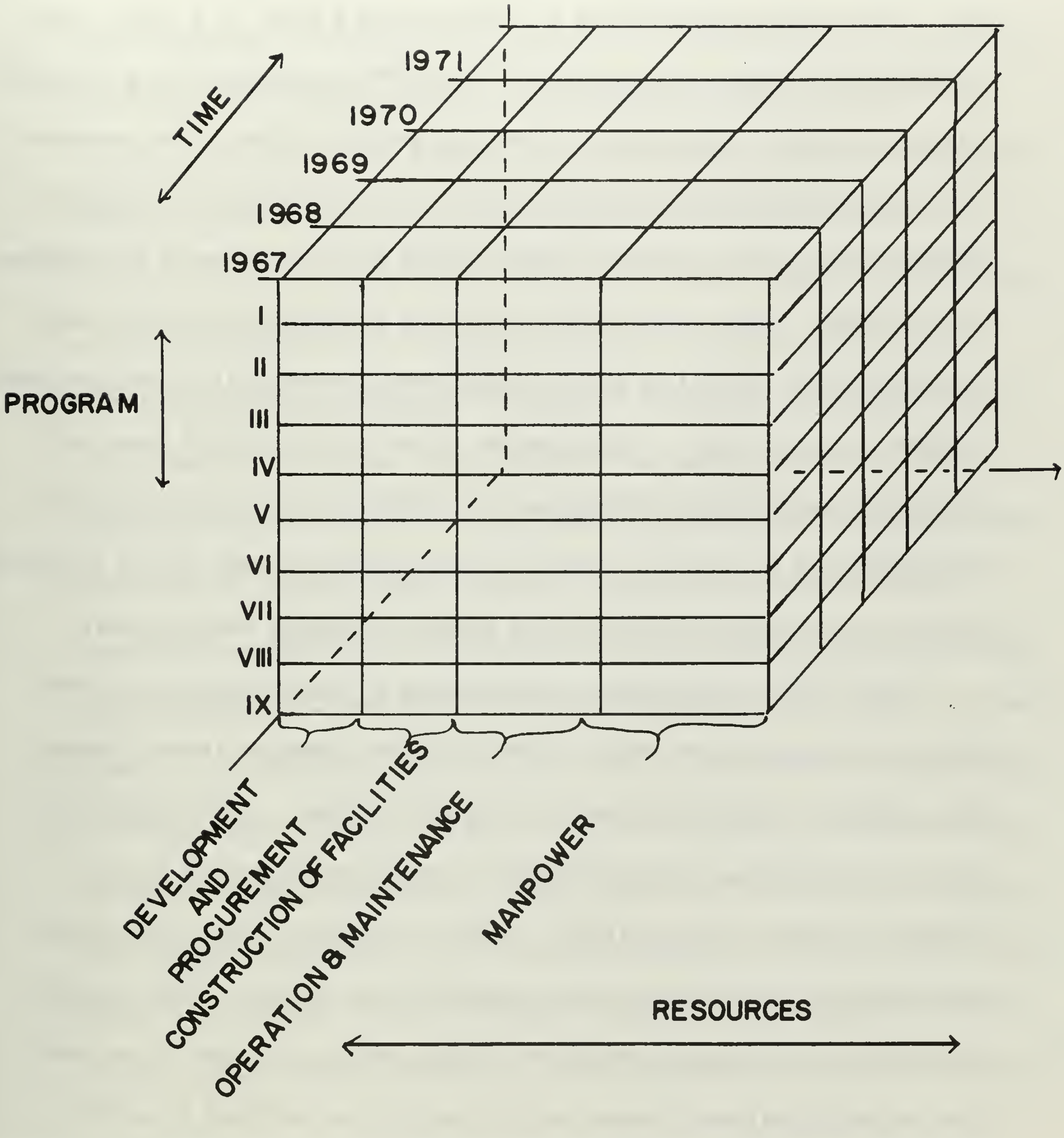


FIGURE I-8 FIVE YEAR DEFENSE PROGRAM

As will be described in the following pages, R&D project proposals are developed by a well-specified sequence of documents. Several of these steps involve R&D effort in the form of feasibility studies and preliminary design. The Technical Development Plan (TDP), which is the last stage prior to inclusion of a project in the FYDP, is a major study of the system under consideration. The TDP represents a large expenditure of scientific, engineering, and cost-analysis effort. The sequence does not normally take five years, however, and therefore a number of projects which are expected to begin within five years cannot be included in the FYDP. Approved projects may have estimated production dates and operational dates that are not much more accurate than R&D projects without final approval. For example, if two projects which have just recently completed the TDP phase, one with and one awaiting approval, the FYDP will include the production and operating funds for the approved project, and exclude entirely those projects awaiting that approval.

The FYDP is continually being updated to reflect approval of new Technical Development Plans (TDP) and other changes; these changes are subject to approval of the Secretary of Defense. The formal document for submitting interim changes in an approved project is the Program Change Request (PCR), formerly Program Change Proposal, and threshold requirements are established for its use. For example, any change in the programmed cost of $10 million or more in one year for an R&D program element, or $25 million for the total program, requires a PCR. The PCR requires detailed costing and a presentation of advantages of the existing program; for a more detailed description of the PCR and related procedures, the reader is referred to SECNAV

Instruction 5000.24, ref. C-25. The Navy requests for changes are reviewed by the Office of the Navy Comptroller for appropriation and fiscal status implications, financial feasibility and balance, validity and reasonableness of costs and pricing, and legality. The Comptroller of DoD establishes standardized terminology, classifications, and procedures for budgeting and accounting use by the services. These are essential for consistency and for use of automated data processing techniques throughout the planning-programming-budgeting process.[25]

The FYDP is supplemented, prior to the annual budget preparation, by lists of requirements submitted by various activity levels to the Secretary of Defense through the chain of command. CNR submits the Navy Research Program; CND submits the Exploratory Development Program; DCNO(D) submits coordinated requirements for the Advanced Development, Engineering, and Operational Systems Development Programs; and these are coordinated and balanced by ASN(R&D), CNO, and the Secretary of the Navy before submission to DoD. These requests usually exceed what can be approved, and are therefore accompanied by a "justification" of each element. The justification is designed to show that the proposal is consistent with procedural and legal requirements, essential to performance of the assigned mission, the most effective and economical method of accomplishing its purpose, feasible with respect to timing and resource availability, and substantiated on its own merits.[26]

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[25] B-18, pp 3-5, 6; 4-4.

[26] Ibid., pp 4-3.

The lists of requirements and FYDP are reviewed by the Secretary of Defense and his assistants in a "mark-up" process of reducing, increasing, or eliminating items. Changes are explained by SECDEF and his assistants by Program/Budget Decision documents, formerly called Subject/Issue papers. There may be several hundred such papers involved in the process of budget formulation, providing guidance for the service activity levels. The military departments may then request reconsideration of their proposals by means of reclama. The reclama may request restoration of all or part of a reduction in budget estimate, or make a more general alternative proposal in response to the Secretary's action. The reclama are reviewed and the revised program is converted to the appropriation structure for the three-year period to be presented in the budget plan for submission to the President and Congress. The program review is the primary means by which DDR&E exercises his responsibilities for coordinating service programs.[27]

The Bureau of the Budget under the Treasury Department reviews, revises, and approves the program submitted by the Secretary of Defense and inserts it into the Executive Budget, which the President presents to Congress. The Executive Budget estimates are considered by the Armed Services Committee and the Appropriations Committees by both the House and the Senate, who hold formal hearings with OSD and service representatives. In FY 1963, the House Armed Services Committee established a separate subcommittee for reviewing the RDT&E

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[27] B-18, pp 4-2--6.

appropriation. The Subcommittee and Committee results are presented to the full House of Representatives and Senate, a final budget is selected and approved, and the approved appropriations are sent to all departments for allocation. Specific Congressional changes are incorporated directly, and the Navy must distribute the general and "spill-over" cut-backs and modifications among the various projects and activity levels.[28]

This is again a complex and time-consuming process: for example, a Congressional across-the-board reduction of the RDT&E appropriation probably could not be applied directly as an across-the-board cut-back of all RDT&E projects. Some projects may have been included at a minimum level, below which it is impossible to operate to obtain any useful output; others may have been funded at a higher level in order to speed the final development but may actually be able to function more efficiently at a lower funding level if the resulting delay is acceptable. All the offices which combined to present the original budget requests must again get together to allocate the available funds. Figure 1-9 presents a summary of the planning-programming-budgeting process as it is applied to RDT&E in the Navy.

Major Navy and DoD Planning, Programming, and Reporting Documents

In order to promulgate objectives for guidance in planning, the Navy and DoD use a number of documents. Other documents are used by the activity levels to propose and implement action in either general or specific response to requirements set forth in the higher level plans.

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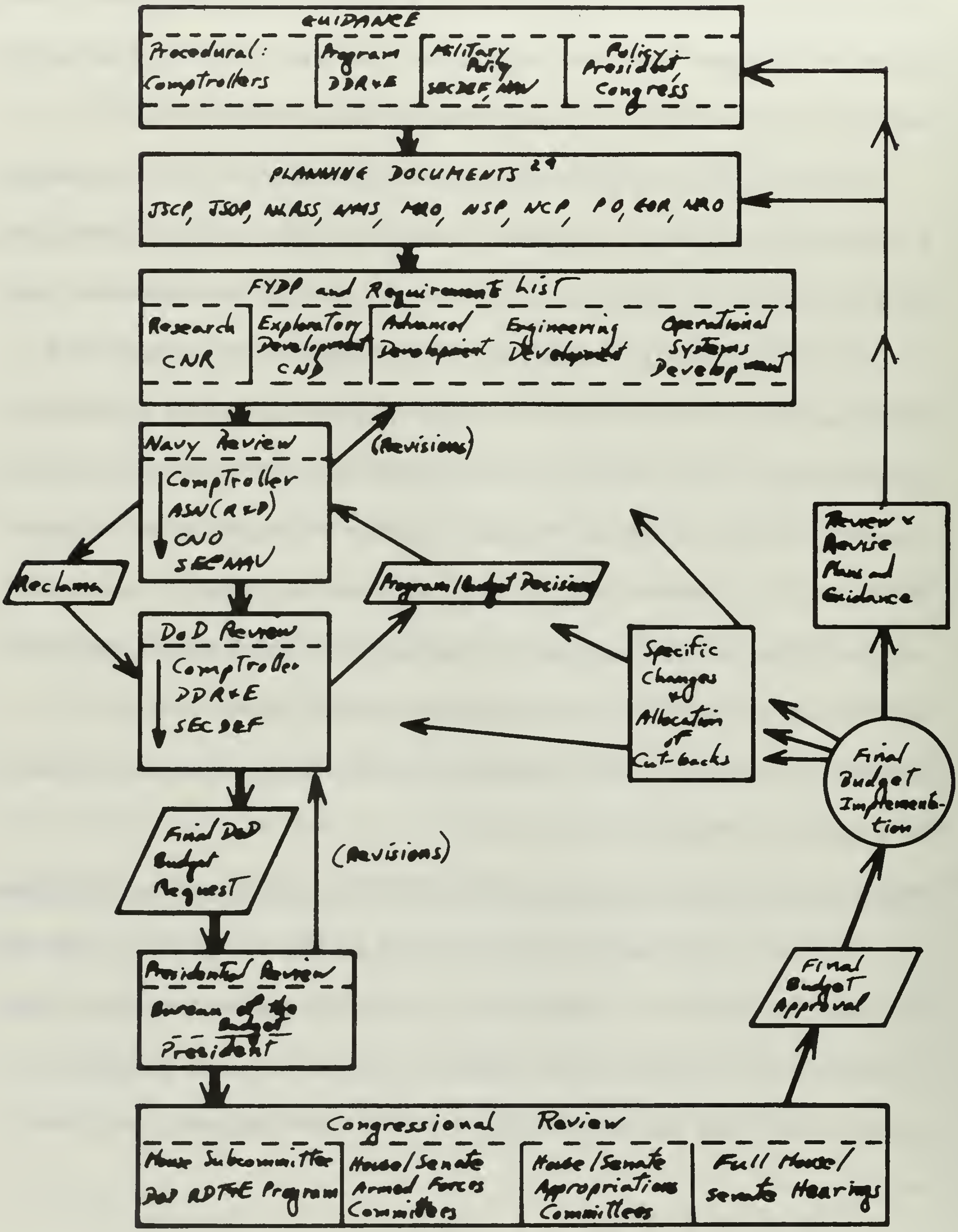
[28] B-18, pp 4-2--6.

PLANNING-PROGRAMMING-BUDGETING FOR NAVY RDT & E

FIG. I-9




[29] These documents are described in the next section

Specific reporting procedures are used to monitor and control the RDT&E effort and to communicate current advances and difficulties throughout the R&D community. These documents are described in this section to provide additional information on the manner in which research and development is carried out in the Navy.[30]

Joint Strategic Capabilities Plan (JSCP-FY). This plan is prepared annually by the Joint Chiefs of Staff to translate U. S. national objectives into short-range military objectives. It includes a discussion of U. S. military position in relation to our allies.

Joint Strategic Objectives Plan (JSOP-FY). This is another annual JCS plan covering the years 5-9 from scheduled date of approval. It is a more detailed and specific document than the JSCP, and is a primary advanced planning input to budget estimate preparations and justifications. It is developed in six parts: purpose, strategic appraisal, military objectives, strategic concept, basic undertakings, and force tabulations.

Joint Long-Range Strategic Study (JLRSS). Covering a period of years 10-13 from date of approval, it provides a broad strategic appraisal for long-range development of support for national objectives.

Navy Long-Range Strategic Study (NLRSS). The NLRSS provides the Navy's input to the JLRSS, but covers years 10-19. It stresses scientific and technological feasibility and probable availability of resources (rather than estimated budget/program constraints).

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[30] These documents are described in greater detail in references C-24, C-4, and C-7. Specific instructions are listed with the descriptions where applicable.

Qualitative force requirements and noteworthy development areas are included. The Director, Strategic Plans Division, under DCNO (Plans & Policy), develops this study with assistance from other OPNAV offices, CNM, and laboratories and study groups in the Department of the Navy.

Navy Mid-Range Study (NMS). This is the input from the Navy to the JSOP and its contents are similar. It is also used in formulating R&D goals. The Director, Strategic Plans Division prepares this study also.

Navy Mid-Range Objectives (MRO). This plan must have been the most difficult one to name: it is prepared by the Director, Long-Range Objectives Group based on NLRSS, NMS, and national objectives and policy, and it concentrates on developing balanced ship and aircraft requirements for the eleventh fiscal year subsequent to its approval. It considers technological potential and derives intermediate shipbuilding and conversion goals to meet the requirements for year 11. Alternate force goals are presented, justified, and the associated risks evaluated. An upper level force structure and associated budget are derived from desired effectiveness levels and technological constraints; a lower level from fiscal and policy constraints.

Navy Support Plan (NSP). This plan is based on approved Navy forces, and estimates the total Navy structure for active and reserve forces for years 1-9. Forces are described in terms of manpower, ships, aircraft, organizational units and shore activities, providing a basis to determine support requirements. One of its components, the

Mobilization Manpower Allocation/Requirement Plan (M-MARP) discusses current readiness and mobilization capabilities, and objectives for these characteristics in the future. NSP is prepared by the Director, Logistics Plans Division under DCNO(Logistics).

Navy Capabilities Plan (NCP). In support of the JSCP, the NCP lists naval forces to be assigned to unified and specified commands, assigns responsibilities for readiness and performance of operating forces, and provides guidance for mobilization and logistics requirements. It is prepared by the Director, Strategic Plans Division, DCNO (Plans and Policy).

Navy Program Objectives (PO). This document is prepared by ACNO (General Planning & Programming), reviewed by CNO and CMC, and approved and promulgated by SECNAV. It states annual increments of balanced force levels required to achieve objectives presented in MRO; increments are in terms of DoD programming categories. PO provides force structure input for JSOP, and guidance for developing PCR's and reclamas to SECDEF force level decisions. Time periods and other aspects of these primary planning documents are summarized in Figure 1-10.

General Operational Requirements (GOR). These are broad statements of objectives for operational capabilities in years 5-15. They are an important input to R&D planning, and serve as an invitation for activity submission of Proposed Technical Approaches (PTA). The GOR are presented in terms of specified functional warfare and support areas.

Figure 1-10
Major Planning Documents[31]

| Abbreviated Title | Years Covered | Originator | Updating Schedule |
|---|---|---|---|
| JLRSS | 10-13 | JCS | --- |
| NLRSS | 10-19 | Dir., Strategic Plans Division | 1 January |
| JSOP | 5-9 | JCS | --- |
| NMS | 5-9 | Dir., Strategic Plans Division | 31 March |
| JSCP | 1 | JCS | --- |
| NCP | 1 | Dir., Strategic Plans Division | 1 June |
| MRO | 11;1-11 | Dir., Long-Range Objectives Group | 15 October |
| PO | 2-9 | SECNAV | Continuous; major update 30 November and 1 March |
| GOR | --- | CNO | 15 October |

[31] C-24, Encl (2), (3).

They are generally reviewed by DCNO's/ACNO's with comment from the Director of Naval Intelligence, published in a single volume by CNO, and reviewed as needed and annually. (OPNAV 3910.9A, ref. C-15.)

Naval Research Objectives (NRO). CNR promulgates this general statement of the need for studies in physical and life sciences to provide information related to a solution of specific practical problems. It provides the structure for programming and budgeting the Navy's research effort.

Exploratory Development Goals (EDG, formerly called Exploratory Development Requirements). CND analyzes GOR's, MRO, NLRSS, and the technological state-of-the-art, establishing the basis for initial investigation required to advance technology in various functional areas. (NAVMAT 3910.4, ref. C-10.)

Tentative Specific Operational Requirement (TSOR). Prepared by CNO and addressed to CNM or other cognizant office outside the NMSE, the TSOR starts the process of defining a system--its characteristics and specifications, and costs for R&D procurement, operation, and maintenance. It is not a firm requirement and does not authorize the start of a new development program. (OPNAV 3910.6B ref. C-12).

Proposed Technical Approach (PTA). The PTA is prepared by CNM or other cognizant office in response to a TSOR or GOR. It serves as a basis for a decision on further development. It includes cost/time and cost/performance trade-off analyses, and appraises technical risk, reliability, maintainability, and support requirements.

Advanced Development Objective (ADO). If the PTA indicates the existence of high technological, financial, or developmental risks, an ADO is prepared by CNO to outline the areas requiring further study prior to full-scale development.

Specific Operational Requirement (SOR). If the PTA does not indicate unacceptable risk, CNO prepares an SOR for CNM or other cognizant office specifying the operational capability desired. It is issued only when inclusion of the expressed capability in the FYDP is probable. Current capabilities and deficiencies in the area are discussed, and requirements in terms of reliability and compatibility are stressed.

The SOR requires a response in the form of a Technical Development Plan, and a decision as to whether the formal Contract Definition phase will be required. Contract Definition (CD) will be initiated for either (1) projects having cumulative RDT&E cost of more than $25 million, or (2) systems for which the production inventory costs are expected to exceed $100 million, but CD may be initiated for other projects as well. (The Contract Formulation (CF) and CD phases were formerly called the Project Definition Phase (PDP).)

Technical Development Plan (TDP). A TDP is a detailed documentation of the actions, procedures, and resources required to achieve the capability defined by an SOR, or the knowledge required by an ADO, and may fill several hundred pages. It becomes an important management control device when the plan is approved by CNO for funding. The TDP includes:

(1) Narrative statement of requirement
(2) Brief development plan
(3) List of performance characteristics
(4) List of reliability characteristics and plans to attain them
(5) List of maintainability characteristics and plans to attain them
(6) PERT/TIME diagram, or similar schedule
(7) Financial plan of project development period, including support
(8) Summary sheets
(9) Management plan
(10) Block diagram
(11) Sub-system characteristics
(12) Associated system characteristics
(13) Operability and support plan
(14) Test and evaluation plan
(15) Personnel requirements and training plan
(16) Production, delivery, and installation plan

A detailed format for the TDP presentation is specified in OPNAV 3910.4B ref. C-11. Due to the magnitude of the effort required for and the volume of the TDP, it is frequently produced by an in-house laboratory or contracted to industry, and the final report includes a "TDP Summary" of information required by higher level management. The TDP and summary are kept up-to-date and reflect approved PCR's.

If the CF/CD phase is required for the particular Engineering Development or Operational System Development Project, the Navy and contractors must exchange ideas on various aspects of the project's feasibility. The Navy initiates the exchange with a Request for Proposal (RFP) which includes requirements, results of previous studies, criteria for proposal evaluation, and work schedules and documentation required for CD. The contractors then submit their proposals, which include lists of and specifications for required end items (including PERT network),a maintenance plan, cost estimates, time/cost/performance trade offs, reliability specifications, technological approach and

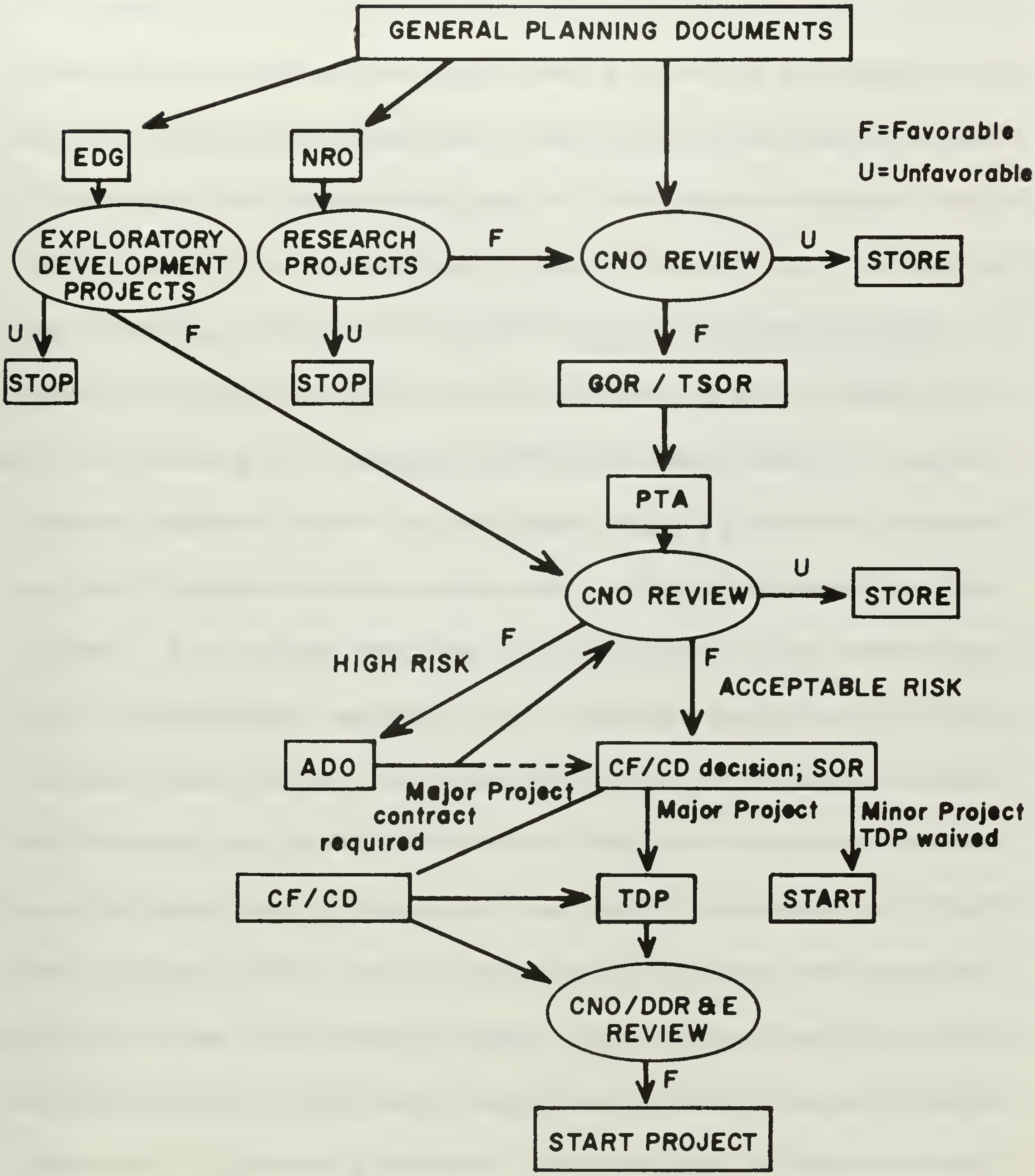
foreseeable problems, management techniques, proposals on specific features of an incentive contract, and several other considerations of import in conducting the engineering development. (SECNAV 3900.33, ref. C-9). A summary of the project growth and initiation process is presented in Figure 1-11.

In contracting for research and exploratory development, the procedures are less elaborate. In-house capability is used whenever practicable. Proposals, many of which are unsolicited, are reviewed by persons competent in the particular technical field (generally from ONR or the office of CND) for feasibility and reasonable practicality. Larger projects require further feasibility and cost-effectiveness studies. The R&D contracts require effective costing procedures and close and continual evaluation of contractor progress and performance. (SECNAV 4200.21, ref. C-22.)

The Navy has adopted formal, standardized reporting procedures to augment the updated TDP's in facilitating a continual appraisal of the existing R&D programs. They are designed to detect deviations from planned performance, cost, and schedules, and to assess and update the current validity of plans and requirements. The concept of "management by exception" is employed, under which higher level management interjects itself only into those situations requiring corrective action. The action may involve requiring events to conform to existing plans, or developing new plans. The following paragraphs describe some of the major management-oriented forms.

FIG. I-II

DEVELOPMENT PROCESS OF A PROPOSED R&D PROJECT



DD Form 1498 Reporting System. This form is used for reporting in the planning stages and for work in progress; it replaced the DD Form 613 system. It is used by the Navy Automated Research and Development Information System (NARDIS), which is designed to store for rapid retrieval specific management, scientific, and technical information required by the Navy and by higher authority. The DD 1498 is used at the RDT&E working levels: the element, the project, the task area, and the work unit level. A copy of DD Form 1498 is included in Appendix C. The NARDIS system is described in detail in ref. C-8.

RDT&E HOTLINE Report. This report is used by activity levels to keep ASN(R&D) and DCNO(D) up-to-date on major advances or problems that may seriously effect the RDT&E program; it is generally used only for problems having a major effect on time, funds, technical development, or personnel support. Other areas may be included if they are expected to result in Presidential or SECDEF inquiry; e.g., labor relations, contractor relations, civic relations, small business, accidents, or reduction in force considerations. Hotline reports are in standard message format and are sent to DCNO(D) for action and ASN (R&D) for information. They may be initiated by telephone, but must be confirmed by message. For each project, the timing, funding, technical development, and personnel support problems are each assigned one of the following subjective evaluations: good shape, minor weaknesses (can be handled by bureau or office conducting the project), marginal, major weaknesses (assistance required from outside the office, but from

within the Navy), or critical ( the Navy must seek outside assistance; e.g., from OSD, other services, or Congress). (OPNAV 3910.13, ref. C-17.)

Research and Exploratory Development Program Highlights. This document presents a summary of breakthroughs and problems from the Program 6 categories "Research" and "Exploratory Development" only; the other reports are used for Advanced Development, Engineering Development, and Operational Systems Development. Reports are submitted on an exception basis; there need not be a report on every project every month. This reflects the fact that work in these two categories does not generally lend itself to exact cost and time scheduling basis. The problems to be included are those which are expected to require changes in the time, cost, or personnel support required for completion, a redirection of emphasis or approach, and major achievements or failure to meet milestones. As in the HOTLINE report, events expected to be of Presidential or SECDEF interest may also be included. While message format is not used, the reports are to be concise, specific, and factual; opinions if included must be clearly identified as such.

Monthly Project Evaluation. This report is required every month for all Advanced Development, Engineering Development, and Operational Systems Development projects. The information in the report is plotted against the TDP planning data to keep ASN(R&D) and DCNO(D) up-to-date. Copies are also sent to other offices of CNO, the Management Information Center, and the Office of the Navy Comptroller.

The primary considerations are timing, funding, technical problems, personnel support, and reliability. The report is brief--only one page--and the information required is well designed to assist management. The entries are summarized below:

Overall Evaluation: milestones, funds, technical development, personnel support, and reliability all rated on the same basis as described under the HOTLINE report
Subsystem Evaluation: subsystems rated in the same manner
RDT&E Fund Changes: expected changes from last approved FYDP, with explanation for change
Remarks: explanation of all items not rated as in "good shape"
Project Highlights: major breakthroughs or new capabilities; milestones achieved this month, estimate of operational date, and personnel training plan required

Quarterly Project Reliability Summary. These reports are required only on projects in the Engineering Development and Operational Systems Development categories. They serve as a reliability annex to the TDP summary by providing minimum acceptable reliability requirements and project reliability goals; they also serve as quarterly progress reports for top management. The reliability summary is in terms of approved minimum acceptable reliability requirements, contracted reliability goals, predicted reliability, and achieved reliability; the data is given for subsystems and for the overall systems reliability. The report concludes with notes on the basis for the reliability figures and confidence levels presented. The report is largely quantitative, with sufficient notes to explain the figures presented.

Several evaluation aids not in the report form are used by management in keeping track of projects in the program. The Monthly Project

Evaluation Reports are summarized with the Research and Explorat[illegible] Development Highlights for a Monthly Summary Analysis, primarily by the Development Planning Division under DCNO(D). Each Monday, except for the first Monday of the month, ASN(R&D), DCNO(D), and senior representatives from CNM and the Bureaus assemble to review selected projects; all projects are reviewed twice annually and those in difficulty more often. Program Status Books are maintained for ASN(R&D), DCNO(D), and ACNO(D), containing current pertinent information from the TDP's.

In response to previous difficulties in meeting schedules and costs, the SECDEF MEMO of 16 August 1961 was issued. This memorandum is aimed at eliminating the bias of meeting specific system or hardware requirements at all costs, and replacing that bias with a more effective evaluation of trade offs of requirements with completion time and total project cost. It states that technical feasibility is not in itself justification for a weapon systems or equipment development, but that the system must be designed to meet a recognized military need. DoD and the services retain responsibility for reviewing and evaluating the trade offs, but contractors are encouraged to present alternative requirements to reduce cost and speed development. (OPNAV 3910.8A, ref. C-14.)

Chapter 2. RDT&E Management vs. Uncertainty

> It is estimated that 100,000 persons a year, whose principal responsibility it is to make judgments as inputs to the decision process, lose their jobs; most of these persons have probably been replaced by algorithms.[32]

The managers of research and development programs are confronted at every decision with uncertainty. The uncertainty comes from a variety of sources: the changing political-military situation, definition of objectives and requirements, the alternatives available and their utility, cost, reliability, and time requirements, the best mix of alternatives to achieve a balanced program, the magnitude of the overall R&D effort required to make the most efficient contribution, and whether Congress will approve the funds requested.

The managers have the responsibility for providing the new equipment, technology, and procedures to improve the organization's ability to meet current commitments and to ensure the capability for meeting future commitments. This requires first that the managers be familiar with existing commitments, capabilities, and problems. To do this in general terms is not an unreasonably difficulty task; but do so with the detail and precision required to make use of conventional mathematical resource allocation techniques is very difficult. Extending the problem five, ten, or twenty years into the future--as the R&D managers must--tends to transform a difficult problem into chaos. To prevent that chaos is the task of the R&D manager.

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[32] A-17, pp 11.

Sources of Uncertainty.

The mission of the organization is a reasonable starting point for seeking a solution to the R&D manager's problem. A general statement of the purpose of the organization is usually available, but it must be divided into more specific objectives to be useful. The next step is to evaluate projects by their contribution to the organization's objectives. For example, the Navy would consider such things as the relative contributions of carrier strike aircraft and Polaris submarines to Program I, Strategic Forces. This evaluation requires an analysis of the current and projected political situation, and is most often done in developing a scenario. But most aspects of the future must remain uncertain no matter how thorough the analysis. There is no intent to discredit a careful study of this phase of the problem. It is simply observed that long-range plans must be based on possible rather than certain events. The XB-70 program is a spectacular example of what can happen when a threat and requirement are re-evaluated. Approximately $1. 5 billion was spent for development before the requirement for the aircraft was ultimately ruled invalid.[33]

Once the scenario(s) is established, the objectives are then evaluated and "reasonable" estimates of requirements made. Even if there were no doubt about the events in the scenario, the requirements could not be determined with certainty because the necessary equipment and operators

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[33] B-25, pp 11.

do not have a reliability of 100% and the exact value of their reliability is not known in advance. Another compromise with reality must be made, and the manager must deal with the particular force level that can probably do the job required by the scenario. These remarks apply even if the analysis is made using available and tested hardware.

Evaluation of proposed systems introduces more problems. A search for alternative projects is made and then each proposal must be studied to determine whether the project can develop a successful product or system, what characteristics the new system will possess, how much it will cost to develop, produce, operate and maintain the system, and how long it will take to acquire an operational system. The manager needs information on cost/effectiveness and cost/time trade offs. Procedures for making estimates of these characteristics and quantities are improving, but a large measure of uncertainty remains.

Various combinations of proposals and current projects must be studied in formulating the complete R&D program, thus further compounding the problem. The interactions between projects cause numerous difficulties. Even in the case of existing hardware, the decision as to whether \$100 of A and \$200 of B is more effective than \$200 of A and \$100 of B must often be a subjective one. Measuring the relative military worth of various systems is an area of utility theory which, for all of the quantitative techniques that have been applied or suggested, remains imprecise. Measures of the return on R&D effort are very difficult to obtain. Many studies have given up on that portion of the

problem altogether, and merely assume that output is directly proportional to input for all projects. With that assumption, "optimal" allocation of research personnel, funds, and facilities becomes highly suspect.

When the manager must deal with research projects that attempt to increase the general store of knowledge in various areas, his problems are multiplied. In the preceding discussions of development projects, the end items of the R&D effort were reasonably well defined. But in basic research, not only does the manager lack information on the cost, duration, and probability of success of projects, but he does not know what useful output will be obtained, if any!

The next problem in conducting an R&D program is reserved for the program's top management, with sympathy. The full spectrum of uncertainty combines with the difficulties of measuring returns on research and development investment to greatly complicate the decision of how to allocate expenditures between basic research projects, long-range development projects, and rapid-return development projects. This dilemma probably accounts for the frequent criticisms of current R&D programs in both civilian and military organizations as being biased toward those development projects expected to give the quickest results. These same difficulties complicate the higher level decision of how much money to allocate to the total R&D program in relation to the other major programs.

Even when the Navy and DoD arrive at what they feel to be the best R&D program, there remains another element of uncertainty: they do

not know whether Congress will approve the funds necessary to carry out that program. The Congressional decision is influenced by international politics and the cold-war situation, national growth rates, unemployment, trends toward inflation or recession, and political log-rolling.

The R&D manager's problems are complex and wrought with frustrations. In reference to the opening quote of this chapter, it would appear that very few of those decision-makers being replaced by algorithms will be involved in R&D management. But to ignore modern management techniques and fly entirely by the seat of the pants is to lose sight of the purpose of those techniques. The techniques are not designed to make the decisions; they are designed to put complex problems into a manageable form to give the decision-maker a handle on the uncertainty and risk involved, the scheduling and funding requirements, and the range of potential returns on investments. Well-formulated mathematical models can be no more accurate or reliable than the assumptions and data that go into them. The same is true of the decision-maker to a lesser degree, but the experienced manager can evaluate details and aspects of the problem that are omitted from mathematical models. The model should be designed to provide an optimal solution if it is available, but in the more common instances an optimal solution cannot be defined quantitatively. The model should make flying by the seat of the pants a more stable evolution.

## Organizing for Research and Development

It is obviously not possible to summarize here everything that has been said about organization structures, policies, and techniques, nor is it intended. But there are some observations concerning the types of organization structure that have been used in research and development activities and some established management policies that should be considered in conducting research and development. The magnitude and extent of the uncertainty inherent in the R&D process demand the best management techniques available. The time required to establish a broad and complete data base to reduce the uncertainty is a luxury that cannot be afforded. Planning procedures must be developed which can account for present uncertainty and which can be easily modified to accept more accurate data. This section suggests and discusses some such management procedures.

Several different approaches for organizing the R&D function of corporations have been tried and tested in practice. Industry has not arrived at any single structure as being generally the best; the different structures have their own advantages and disadvantages which must be evaluated against the type of research to be conducted. The American Management Association sponsored a study of R&D organization structures and the results of that study are summarized in the next four paragraphs.[34]

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[34] B-58, pp 24-40.

Subject/Discipline Structure. Organizing the R&D function according to subject is a useful technique when much of the work can be readily assigned to the subject areas; it is done in the Office of Naval Research. It facilitates coordination and communication within the subject area, and makes it easier for the scientists and engineers to keep abreast of new developments in their field. It provides flexibility and comparative ease of assigning both priorities and personnel, and in shifting them as necessary. Project selection may be made with more complete knowledge of the alternatives. Continuity of research is enhanced, and greater advantage is taken of learning curve benefits. The characteristics which produce these advantages become detriments when the organization must undertake multi-discipline projects. An additional difficulty which occurs even without the multi-discipline problems is the tendency toward narrow outlooks resulting from overspecialization.

Product/Type Structure. This type of breakdown is more commonly found in the development end of the spectrum, where multi-discipline problems are the rule. For large organizations, the product type may be subdivided on a subject basis; the net result is a series of line units organized on a product basis, supported by staffs from the required subject areas. This requires great flexibility of personnel assignment. . The project/type structure groups the necessary people together in a team to conduct a coordinated attack on particular problem types, and develops a set of technical information and solution techniques. It makes it more difficult for scientists and engineers to keep current in their

fields. It also raises objections from scientists and engineers because of the need to shift personnel between products, allegedly creating feelings of insecurity and uncertainty.

Project/Problem Structure. One of the most frequently employed structuring techniques for multi-disciplinary work is to form problem-solving teams within a laboratory or other organizational unit. It provides stimulating interaction between scientists and engineers. The periodic shifting of personnel is considered to be an advantage when it can be done within the lab, thus eliminating major readjustment for the individual. Its other advantages and disadvantages are similar to those discussed under the product structure.

Stage/Phase Structure. Division of the organization along the R&D spectrum is often made at the top levels of the R&D organization to group functions with similar uncertainty characteristics. Each of the broad categories is then subdivided using one of the three structures presented above. This broad division has the disadvantage of complicating transfer of knowledge--and problems--from one phase to another.

In terms of the Navy's R&D efforts, the phase structure is used in placing Research under the control of CNR, Exploratory Development under CND, and Advanced, Engineering and Operational Systems Development under DCNO(D). The subject structure is used within ONR. Analysis of the development effort is more difficult. The research and development offices within CNM and other organizations have a line responsibility in conducting R&D and a staff function in

using R&D to support the mission of their particular activity. Development is structured on what is, roughly speaking, a product basis; e.g, ships, weapons, or medicine and surgery. Within each Bureau or major office, the organization of the development effort is structured once again, this time on more of a problem basis.

The Navy also uses the project/problem structure for special projects of high priority as selected by the Secretary of the Navy. The use of project management has received some severe criticism from Navy sources in spite of its demonstrated success in the development of the Polaris-FBM system. It has a tendency to siphon off the elite management talent for special projects, leaving the rest of the R&D program in less-experienced hands. Its increased use was cited by Rear Admirals Brockett and Curtze as one of the reasons for their early retirement from the Bureau of Ships, because it was undermining the importance of their functions in the Bureau.[35] It may be that the Navy is misusing a good thing by placing project management outside of the control of Bureau Chiefs. It is probable that if the Bureau Chiefs and CNM were given the authority to use project management at their own discretion, many of the same problems would generally be designated special projects and the system would function more smoothly. Then if a high priority were deemed necessary, SECNAV approval could be solicited.

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[35] B-56, pp 20, 25.

Another important management consideration is the degree of centralization or decentralization which should be built into the organization. It is again difficult to make definite conclusions in favor of one extreme or the other. The policies followed by the American Cyanamid Company in this area indicate the nature of the problem,[36] and are described in this paragraph. Initially the company employed a decentralized and loosely coordinated R&D structure, with each division operating nearly independently. Communications were informal and sporadic; "...the inevitable duplication actually stimulated some effective internal competition, but more often the results were less than favorable."[37] In 1954, all research programs were centralized and work on each product was consolidated in one location. A cooperative spirit was generated within each product group, but the managers of operating divisions no longer felt any direct responsibility for research and development, and the research activities lacked commercial guidance, e.g., in estimating market potentials. The company decided to return the R&D function to managers of the operating divisions, making them responsible for both the current and future operations of their units. Other companies have undergone similar transitions, but starting and ending with a centralized R&D organization.

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[36] B-68, pp 31.

[37] Ibid.

At the risk of oversimplifying the problem it may be viewed as a trade off between the efficiencies of conducting R&D in a centralized location, and the problems of communicating the needs and problems of the operating forces and the potential of the research activity. The Navy weights the trade off in favor of the decentralized structure, but retains some of the advantages and disadvantages of both types. First, the Navy has the mission of contributing to the defense of the nation and its principles. It must have a centralized structure to be prepared to carry out its duties in wartime. On the other hand, top-level management does not have the time to oversee every detailed evolution; it must set up and promulgate objectives, and to a lesser extent, procedures, and then delegate authority to carry out action as necessary to meet the objectives. The usual emphasis on procedures is directed primarily at administrative standardization; when it aims at specifying exactly how every operation should be carried out, it tends to generate such a large volume of reading material that it is self-defeating.

The planning documents discussed in Chapter 1 are a step toward specifying objectives. The documents should be promulgated to all the people who could benefit from their availability. The Navy policy of "management by exception" is an indication of the trend toward decentralization; activities function independently once their course of action has been agreed upon, and higher levels need act only when events deviate from the plan. This policy is acceptable as long as top management participates actively in promulgating objectives and formulating

the initial plans for meeting the objectives. The decentralization is desirable to the extent that it frees top management for top-level decisions, but it can be effective only to the extent that all levels are familiar with the organization's objectives, capabilities, and problems. This is primarily a communications problem. The combination of decentralization and poor communications prevents timely decisions and prompt implementation.[38]

Closely related to centralization/decentralization considerations is the problem of selecting appropriate decision levels; i.e., determining who is best qualified to make which decisions. It seems logical that the managers of the activities actually conducting the R&D and the scientists and engineers themselves would be in the best position to decide which projects to undertake and how to carry them out. This theory is advocated by many managers and management science text authors. The thory runs into difficulty finding people who actually perform R&D and have a good feel for the objectives, requirements, and problems of the organization.[39] This emphasizes the importance of top management keeping all levels informed of objectives, requirements, and problems. The theory is good--it just needs attention to make it work.

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[38] B-1, pp 9.

[39] B-50, pp 74. From a presentation by F. L. Ashworth, USN, Assistant Chief of the Bureau of Naval Weapons for RDT&E, to the Sixteenth National Conference on the Administration of Research, September 1962.

A wealth of material has been written about personnel administration in R&D. Much of it centers about two stereotyped characters: the wizened, bespectacled scientist, obsessed with his specialized specialty, and violently opposed to everything that the other character stands for; the other character is the miss-placed Prussian style R&D manager, issuing orders in great volume and detail concerning matters about which he knows little, and intent upon persecution of the scientist. While this is an obvious overstatement of conditions, it is worthwhile to look at the problems which give rise to these impressions.

The research workers need an environment of academic freedom, in which creativity and initiative are encouraged. They resent being told exactly what they must do, and appreciate a choice in what they do and how they do it. There are many talented people in this business and they are capable of making a contribution to the planning function. But in order to take advantage of that capability, the managers must expose the scientists and engineers to the problems of the organization, attempt to interest them in the problems, and maintain that interest and enthusiasm for the duration of the project. On the other hand, the research workers must recognize the manager's problem of limited time, money facilities, and organization interests. An atmosphere of team work and cooperation is as essential in R&D as in any other field.

The interests of management and the scientists regarding flexibility of personnel assignment and temporary transfers are also discordant. This is a subjective consideration that must be made by management

in allocating personnel and shifting their assignments.

In scheduling work for a particular R&D activity, the manager should keep in mind Parkinson's law that "work expands to fit the time available for its completion." As a group nears completion of a project, the manager should have another project waiting. His attention to the transition to the new project can pay great dividends in time saved. Wachold emphasizes this point in his study of a government R&D field activity.[40]

An organizational institution which must be included because of its extensive use is the committee. It has been said that a camel is a horse that was put together by a committee. The primary objections to committees are that they permit a diffusion of responsibility and lack of accountability; they are conservative in that resulting action is reduced to the lowest common denominator of agreement; and they tend to delay and stifle action.[41] They exist, in spite of the drawbacks, because it is frequently necessary to consult people in different activities about new developments or brief them on new problems or policies which require study by persons trained in disciplines not grouped together any where in the organization structure. They serve as an aid to communications in bridging the gaps between divisions of the organization.

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[40] A-11, pp 270; B-64, pp 1.

[41] A-10, pp 43.

Communications in the R&D Organization.

The need for effective two-way communications has already been stressed in terms of communicating organization objectives and problems, and the capabilities and potential of the R&D activities. It can be readily seen in the exchange of ideas involved in the planning process described in Chapter 1. It is essential to effective control of work in progress. If progress reports are not timely and accurate, the decision-making process must suffer. In a study of information flow in ONR, it was observed that "the bulk of the information actually flowing into the program management decisions is not formal, documented information."[42] The extensive use of informal and personal communications is not a fault in itself, but in the interests of accuracy and obtaining a sound basis for decisions, it must be followed up by more formal documentation. The written project description and information becomes especially critical when a project progresses to the point of more detailed development; without it, much unnecessary duplication of effort is likely. The degree of decentralization in the Navy R&D structure requires a large volume of information transfer.

The final reports on studies made by CNA and other activities, and the TDP's compiled by offices in the NMSE and by contractors present another communications problem. The reports and TDP's are usually

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[42] B-60, pp 53. Quoted from the "Phase I Report, Information Flow at the Office of Naval Research," pp III-2.

very long, and the reports, particularly, are often written to management rather than for management. The originator relies heavily on the oral briefing to assist management in understanding the written presentation. The contractor-originated documents are designed to sell, and the manager must probe beneath the salesmanship to determine the value of the proposal. There is a tendency of the analysts to become so fascinated with their model that they may lose sight of the problem solution that they are trying to present.[43] Computer programs are often included without adequate description and explanation, and if the program is an essential portion of the study the manager has a very difficult time familiarizing himself with the abbreviations and quantities used in order to discover what is actually going on in the program.

The assumptions employed in the analysis determine the validity, interpretation, and applicability of the results. Unfortunately the assumptions--if stated at all-- are sprinkled throughout the report rather than collected for easy review and evaluation. The effect of the assumptions on the results should be discussed in the report. There are numerous lists of the proper ingredients of these reports. One of the more concise is as follows:[44]

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[43] B-65, pp 4.

[44] B-31, pp 160-161.

(1) purpose(s) of the study
(2) definition and brief description of the system
(3) type of costing techniques used (and source of data if applicable)
(4) costs excluded
(5) discounting technique used (if any)
(6) time phasing of project
(7) restrictions and limitations

All of the analytical portions of a report should be described and presented in such a way as to permit evaluation of the project effort after its completion. This phase of management has received relatively little attention, and the bulk of the post-operational evaluation that has been done has been more concerned with the data itself than with the way it was acquired and utilized. Even the data has been difficult to assemble because of changes in schedules, changes in measuring techniques, and changes in the item being developed. This problem should be recognized and eliminated by more careful presentations. The Navy report forms are relatively new and most of them are revised as management uses the reports and gets a better feel for what information is required. They are improving, but a review of the entire reporting system for consistency, redundancy, and omissions would be helpful.

Another type of communications problem results from the wealth of technical literature being published, a problem that is being aggravated by the attempt to measure scientific output by the volume of published material. This greatly magnifies the difficulty of keeping up-to-date on the latest developments in a particular field. The problem can be partially solved by allowing time for reading by both the research workers and managers, by providing the pertinent literature and

abstracts, and by utilizing the Defense Documentation Center. But this may not be sufficient. It may be advantageous in the long run to provide an R&D information service which would maintain a subject listing of articles and reports, compare the listing with activity interests and their current and scheduled projects, and provide a printout of the literature of probable interest to each activity. Since "gaps" of any sort arouse concern in a near-magical fashion, the importance of this problem may be best emphasized as the need to close the ACTION GAP --the painfully slow decision process of transforming scientific achievement into useful products.[45]

An information theory study of the rate of transmission of information throughout the Navy RDT&E community is another project that would no doubt prove interesting. The problem of the distribution of the information--getting information to the people who need it and sparing those who are not concerned--also deserves study. The manager's span of control (the number of his direct subordinates) should theoretically be kept small (about 4 or 5) to permit the manager to properly control and communicate with his subordinates,[46] but this adds to the decision levels of the organization and makes vertical communications much more difficult. Management must decide where it can best control the more difficult communications problems.

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[45] A-7, pp 341.

[46] A-11, pp 173.

The organization and communications problems are intimately related. The manager requires information on operational problems and research potential to produce the objectives and plans that the research personnel need for guidance. Another exchange of information is required in developing ideas into products that assist in fulfilling plans and meeting objectives. Additional communications are necessary between the Research, Exploratory Development, Advanced, and Engineering and Operational Systems Development categories to provide cooperation and mutual support. Research personnel require external information to keep abreast of the latest developments in their fields. They must use effective communications in reporting their work so that management may recognize its implications, convert the results into production items, and evaluate the analytical and managerial techniques that went into the research and development project. Brief and concise reports are helpful to the managers and to the rest of the R&D community.

## Chapter 3. The Initial Planning Process

> We have passed through the age of random creativeness and are entering the age of deliberate creativeness.[47]

In promoting deliberate creativeness, it is necessary to gather information and thoughts to build a base for deciding what directions creativity is to take. A realistic evaluation of current threats, commitments, and capabilities must be made. An attempt must be made to predict future threats and commitments and the ability of current and project forces to meet them must be evaluated. The conclusions must be studied in the light of broad national and organizational policy and objectives, and transformed into more specific objectives. This must be followed by a thorough search for alternative means of achieving the objectives. The alternatives should undergo an initial screening for desirability and feasibility. This sequence of events is covered in this chapter.

### The Scenario.

The procedures for conducting the planning and study outlined above already exist and have been described in Chapter 1. The portion that deals with evaluating current capabilities--the starting point in constructing a scenario--receives little emphasis. It is certainly

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[47] B-48, pp 23. E. P. Stevenson citing a previous conference speaker, Dr. Maurice Nelles.

reasonable to assume that the top DoD and Navy officials are familiar with the capabilities, strengths, and weaknesses of their organizations and that they consider these in formulating long-, medium-, and short-range plans. The program/budget requests submitted to Congress, modified to reflect Congressional changes and the resultant service changes, should be a useful document for this review. Current policy and short-range projections are available from the President's State of the Union presentation, the legislative and executive review of the Defense budget, the Secretary of Defense program/budget decisions, and other sources.

Future threats and commitments are frequently addressed by extensive long-range studies conducted by the Institute of Naval Studies (INS) in CNA. These studies attempt to define and resolve political issues, predict their effect, and assess their military implications. The extent to which the INS studies are compared with similar studies conducted by DoD and the State Department is not clear. The Navy should be responsible for evaluating the implications of the studies for naval warfare, and it is entitled to its own opinions on the other aspects of the studies, but it does seem desirable to determine the differences between Navy-originated predictions and those of other offices. This type of comparison could help to explain and resolve some of the differences of opinion that appear months later in budget proposals.

In presenting the estimate of the threat and evaluating its military implications, a year-by-year breakdown would be most useful. By including intelligence reports and estimates of the enemy research and development capability, this type of presentation facilitates the planning of our own efforts and the assigning of values to our effort. The timing of R&D projects is a very difficult process. Estimates of project completion have been notoriously inaccurate, and the errors have almost always been in underestimating. Any information that can be developed to guide the timing of R&D projects would be a major contribution to planning the allocation of effort.

The primary considerations in the scenario involve the prospects of nuclear and limited war, shifting alliances, and trends in the behavior of under-developed countries; these must be studied in great detail. But non-politico/military topics such as national manpower availability, scarcity of resources, and technological advances are also important. The research and development community should provide the technology predictions. In addition tohelping formulate long-range plans, they would be stretching their own horizons. The latter would help balance the natural tendency to weight the R&D effort heavily in favor of short-range, quick-return projects.

Plans and Objectives.

Using the evaluation of current capabilities and policies, the scenario and the broad national and organizational objectives, the planning process described in Chapter 1 is carried out as a continuous

task, and the scenario must also be updated as major changes in the political situation occur. The plans are officially updated at least once a year, but the process cannot be geared entirely to a one-shot annual review. In developing the plans, probable enemy response to our actions must be considered; the current anti-ballistic missile quandry is an excellent example. It is advantageous to anticipate this sort of problem and have well-formulated alternative courses of action prepared.

It is interesting to note the interplay between the planning documents discussed as separate entities in Chapter 1. Figure 3-1 displays some of the interactions and may help bring the activities discussed in this chapter into perspective. The plans are clearly not independent; they build from current capabilities in the directions indicated by the broad objectives and the scenario, and lead to the formulation of more specific objectives. The MRO specifically plans in terms of an upper level of effectiveness with technological constraints and a lower level of effectiveness with expected budgetary constraints. General recognition of both constraints is apparent in other documents as well.

The formulation of the more specific objectives is essential. Implicit goals lead to inconsistency, lack of coordination, and unavoidable suboptimization.[48] The objectives would be most useful if expressed as desired capabilities. This would provide the research and development community with general guidance and a reasonable degree of

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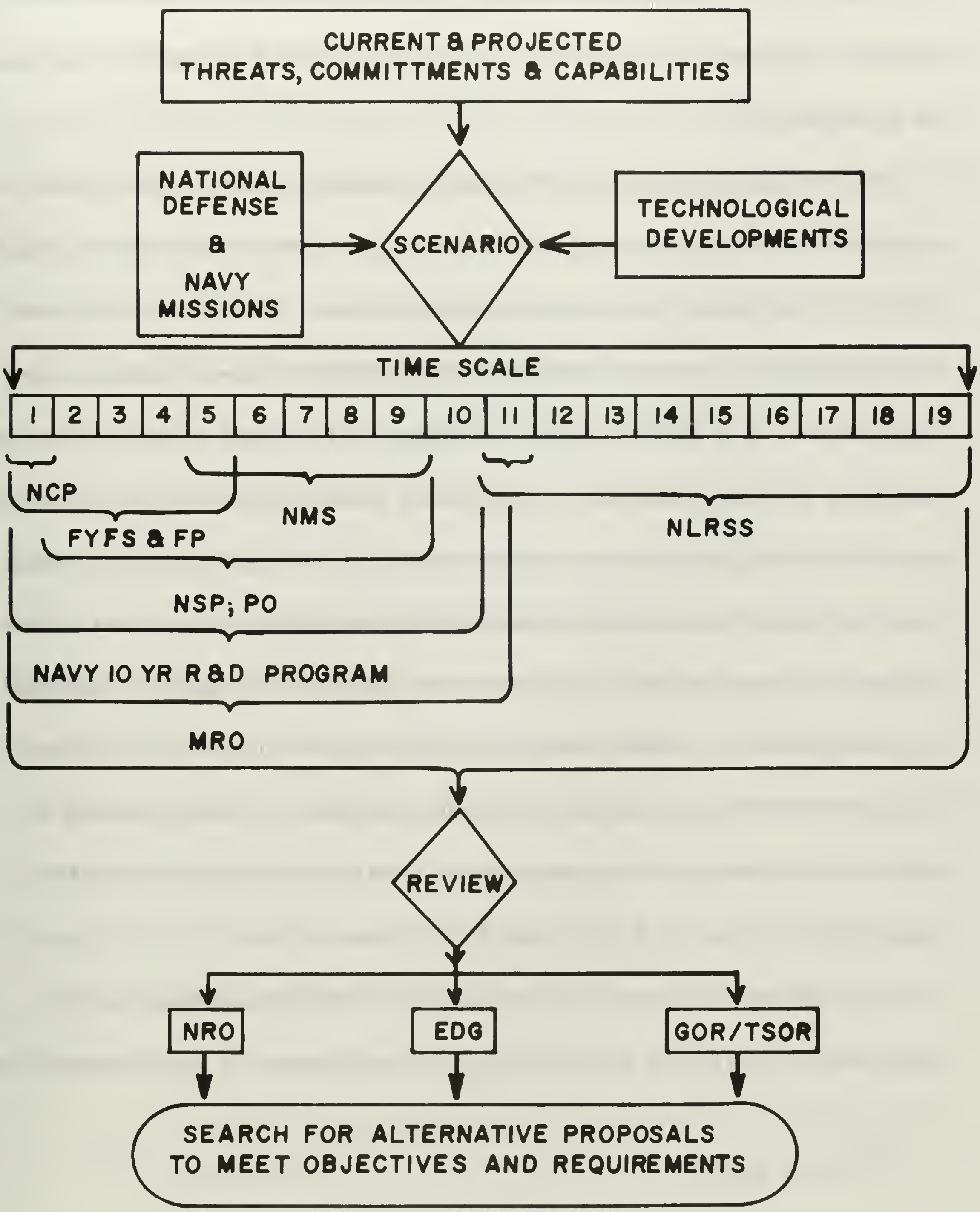
[48] A-11, pp 69.

NAVY PLANNING PROCESS

FIG. 3-1



freedom in seeking alternatives, as well as a responsibility to conduct a thorough and imaginative search for those alternatives. But a simple list of desired capabilities and objectives is not enough to enable the R&D managers to efficiently guide the efforts of their activities. It is not reasonable to assume that all of the objectives in such a list are equally important: "...goals...not only can be arranged; they must be arranged."[49]

There have been many attempts in utility theory to transform the subjective evaluation conducted by managers into some sort of quantitative or qualitative preference relationships. "Reference gambles" are sometimes used to develop dollar values for sets of objectives or capabilities, and several other techniques are being studied. But for purposes of this presentation, the most suitable approach is to require top-level management to provide a numerical weighting of the importance of objectives to approximate their subjective evaluation. This attempt to quantitatively reproduce the subjective judgments applied by management is better adapted to the formulation of the problem than procedures such as the reference gamble. A check should be made on the manager's approximate quantitative values to ensure transitivity; i.e., if $A > B$, and $B > C$, then $A > C$.

A deficiency of most mathematical techniques applied to the quantitative measures that limits their usefulness is that the techniques

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[49] A-6, pp 219.

require independence of objectives. The independence requirement may be met by combining dependent objectives into groups of independent aggregate objectives.[50] But in most of the problems of interest, the number of interdependencies would require such a high level of aggregation as to make the problem unmanageable.

For example, in the problem of selecting an "optimal" deterrent force, Polaris, Minuteman, and B-52's may be among the alternatives. By questioning experienced officers in the Navy and Air Force, it may be possible to assign relative weights to the effectiveness of each missile: Polaris = 10, Minuteman = 15, and B-52 = 5. If the assumption of independence of effectiveness is made, the total effectiveness of 90 Polaris missiles, 100 Minutemen, and 54 B-52's is (90) x (10) + (100) x (15) + (54) x (5) = 900 + 1500 + 270 = 2670. Are 10 Polaris missiles 10 times as effective as 1? Or 5 times, or 20 times as effective? Only if the effectiveness of each missile is independent of each other missile can their effectiveness be added directly. Can equivalent forces be composed of 2670/5 = 267 Polaris missiles, 2670/15 = 178 Minutemen, or 2670/5 = 534 B-52's? If it is reasoned that the enemy must deploy a more extensive and expensive defense in coping with a mix of the weapons, then the answer to the question is "no," and the offensive systems are not independent.

[50] A-4, pp 328.

If the weighting of objectives can reasonably be achieved at the top levels of the organization, subsequent levels of management will then have a very helpful frame of reference for evaluating their objectives. The more specific objectives derived at each level can be evaluated on their contribution to higher level goals. This "subjective quantification" is not very precise, but with the abundance and magnitude of uncertainty that must be dealt with in approaching R&D problems, the lack of precision--while desirable--is not critical.

The search for means of objective quantification sometimes introduces the behavioral concept that implies "objective is to rational as subjective is to irrational"--a most un-objective contention. There are a great many successful managers that rely on their own subjective judgments every day, and it is unlikely that they have been successful because they have behaved irrationally.

Even when the above sequential weighting of objectives has been performed, the R&D manager's problem of allocation of effort has not been completely solved. The allocation of effort is a function of the importance of the objectives <u>and</u> the relative efficiency of research in various subject areas. The inclusion of efficiency brings up the difficult problem of measuring the returns on research once again. That discussion will be postponed to later chapters.

<u>Search for Alternatives.</u>

Up to this point, the current situation has been evaluated, a scenario constructed, general plans formulated, and specific

objectives derived and weighted. The next step is to conduct a thorough and extensive search for alternate methods of achieving the objectives. This responsibility and its full recognition by the R&D community are essential to the entire program. The search for alternatives must include a thorough search of the topic literature. Much effort can be wasted in the name of creativity and originality if the effort is not preceded by collecting information on what has already been done. This tendency is most pronounced in model-building analyses where not long ago it was possible to embark on a project with a very high probability of coming up with an original result. The high volume of unorganized literature makes the search process a difficult one even when undertaken conscientiously.

The search for alternatives is an area where considerable improvement may be possible for a small expenditure of effort. There are many potential sources of proposals. They may originate as specific suggestions from top management or lower level managers, although the managers tend to shy away from being specific in making their proposals because they do not want to deprive the scientists and engineers of academic freedom. There has been some criticism of the services in the past for having told their study groups and R&D organization what to prove, invent, and develop, down to the last minute detail, and the present attitude may be an over-correction. The top levels of Navy management could suggest very specific ideas to be included in the full set of alternatives under consideration at the

appropriate activity for achieving a particular capability, thus providing the benefits of its experience without unduly restricting academic freedom.

The operating forces constitute a largely untapped source of proposals for areas requiring study or corrective action and for possible approaches to the problem. The proposed alternatives from the fleet become more and more effective as the training level of officers is increased through postgraduate study. The Navy has a tendency to rely heavily on its transfer of personnel from ships to particular shore billets to provide the input from operating forces to the R&D process. While the rotation system does contribute to communications, it is not an efficient means of obtaining information for timely decisions. There are other means currently used to obtain a fleet information input; e.g., through the Navy Research and Development Review Board and the Beneficial Suggestion policy of BuShips. But the former is not likely to have time to review a very wide range of alternatives; its review must be performed after a considerable amount of selection and rejection has been completed. The Beneficial Suggestions are too restrictive to support the wide range of subjects in the R&D program.

It appears desirable to have the operating forces provide proposals of problem areas and possible solutions. (Solutions would not have to accompany problem descriptions.) This would be one means of obtaining a higher return on the Navy's training investment, and could stimulate a healthy concern not only for keeping the ships running for

another day, but for substantial long-range improvements as well. For example, a gunnery officer on a destroyer which has recently participated in numerous shore-bombardment assignments may talk to the Marines they were supporting, and conclude that perhaps naval guns--little used for their designed purpose of ship-to-ship combat--could be modified or replaced to achieve a more effective shore-bombardment capability. The Commanding Officer of the destroyer might be sold on the idea after a wardroom discussion, and a brief description of the proposal could be sent off to the clearinghouse for consideration. Thus an idea which might otherwise easily have retired with two or three officers may become a valuable addition to the Navy's capability.

In the interest of rapid communications, it would be desirable to submit the proposals directly to a designated clearinghouse rather than through the entire chain of command. The clearinghouse should provide consolidation and screening services of Navy personnel, scientists, and engineers. This would spare the operating forces' chain of command from an excessive addition to their already substantial paper-shuffling load. The clearinghouse should specifically not be required to explain and describe their disposition of proposals to the originators, although recognitions of exceptional proposals would be desirable.

If it is desirable to obtain from the operating forces a wider range of opinions on proposals, this should be done on a "copy to the chain of command" basis. Highly formalized structure and format for the procedure are undesirable. Endorsements from the chain of command

need be no more than a legible "forwarded," or brief comments such as "looks good" or "would cause problem x," but more detailed comments or additional alternatives could also be appended.

The greatest number of proposals originates in the R&D community, where most of the Navy's scientific and engineering talent is located. The clearinghouse discussed above may be best located in the same place to take advantage of that talent. The specific location is a more difficult problem. Sections III, IV, and VI of the Office of Naval Research constitute one possibility; the office of DCNM(D)/CND and the office of DCNO(D) are others. In the process of soliciting proposals from the operating forces it would be possible to define categories of proposals to be directed to each of these offices. The boundaries between the categories of the R&D program are not well defined and a knowledge of what has been and is being done in each area is required to accurately determine the proper address for a proposal, and the operating forces are not likely to have this detailed knowledge. It may be desirable in the long run to add one more office in spite of the disadvantages of increasing the size of the organization.

Another major source of proposals is external to the Navy: the universities, non-profit research institutions, and industry. Nearly all of the university research supported by ONR results from unsolicited proposals.[51] The solicited proposals may be in response to Naval

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[51] B-62, pp 48.

Research Objectives, Exploratory Development Goals, or Requests for Proposals, depending on the R&D category. The possibility of providing universities with lists of subjects based on some of the alternative proposals collected by the clearinghouses warrants investigation. A very brief list is available at the Naval Postgraduate School to students in the Operations Analysis curriculum under the title "Suggested Thesis Topics." This approach could prove helpful in narrowing the list of alternatives requiring in-house study and Navy financing. Industry is even more susceptible to a similar approach. The research activities attempt to interest companies in undertaking preliminary studies in subject areas related to the company products in the hopes of landing a substantial follow-up contract. Some "seed money" is available for this type of preliminary work without the usual requirement for formal advertising.[52] The proposals answered by the universities may provide an indirect recruitment program for Navy in-house labs as well.

In the context of the existing organization, the offices designated as proposal clearinghouses should consolidate proposals according to subjects and eliminate those proposals which are obviously undesirable, unsafe, technologically infeasible, or which would create more problems than they would solve. The undesirable, unsafe, or problem-generating proposals may be discarded permanently. The technologically infeasible proposals may be collected at ONR or the office of CND for

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[52] B-18, pp 7-12; B-66, pp 5; B-62, pp 48.

further evaluation. If they appear to offer a substantial contribution to the organization's objectives, they may be included at some future date in the appropriate research or exploratory development program area.

The transfer of a proposal for technologically infeasible hardware to the research or exploratory development categories is only one of several exchanges of information between categories. The results of completed basic and applied research must be transmitted to the exploratory development category for evaluation and possible inclusion in the set of alternatives, and similarly for completed projects in each successive category. If a major problem is encountered or at least foreseen in the engineering or operational systems development categories, the entire project may be designated as an advanced development project by existing procedures. Similar (but not necessarily formal) transfer procedures are necessary to permit problems encountered in any development category to be passed backwards through the system for evaluation and possible solution. The ability to attain a flexible and timely mutual support capability between categories is essential to the R&D process. The need for timeliness of this support and of all communications required in the initial planning phase is emphasized by the short life of new products and the long lead time necessary to develop replacement products.

## Classification of Alternatives.

The initial phase of formulating and conducting the R&D program was described projecting national and organizational objectives, current

capabilities, and technological advances into a scenario to devise plans, requirements, and specific objectives for achieving the Navy's mission. The requirements and objectives generate a very large number of alternative proposals and problem areas; it was suggested effort should be devoted to increasing the number of such proposals. This may appear to be an excellent means of making an already difficult task impossible. But encouraging a thorough search for alternatives has several advantages which outweigh the difficulties it would introduce. The advantages are (1) increased sensitivity of the R&D effort to fleet requirements and problems, (2) improved chances of finding the "best" solutions, (3) improved chances of discovering solutions and techniques which may already be available, thus providing a rapid improvement of operating conditions, (4) grouping related problems and proposals which may then be handled more efficiently than as isolated problems, and (5) identifying other interdependencies to improve coordination of effort.

The question is, what is to be done with the vast collection of proposals? The proposals must first be classified in manageable groups. At present most proposals are originated by the activities in response to NRO, EDG, GOR, or TSOR, and the need for classification and forwarding for assignment is less pronounced because the originator expects to conduct the proposed R&D. Classification is carried out for planning and budgeting purposes. The nine major programs and the six categories of the R&D program (6) have already

been introduced. Further divisions are "aggregations" and "program elements." The aggregation is a major subdivision of a category and consists of a number of program elements within the Advanced Development or Engineering Development categories. The program element is the smallest subdivision of the RDT&E program considered in the OSD system, and may be a single project or a number of projects in a related field and in the same budget category. An example of this classification is shown below.[53]

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6.  32.  03.  09.  2
|   ||   |    |    |
|   ||   |    |    └Arm of service (Navy)
|   ||   |    └Element (hydrofoils)
|   ||   └Aggregate (underseas warfare)
|   |└──Dept of the Navy (includes USMC)
|   └Category (advanced development)
└──Numbered program (research and development)
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Figure 3-2
Classification System

Additional classification is required for reporting purposes of approved projects. Each DoD RDT&E project is identified with a class of effort as follows.[54]

Applied Research (AR)--application of knowledge, material, and/or techniques directed toward a solution to an existent or anticipated military requirement

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[53] B-25, pp 2.

[54] C-7, Att 2 to Incl (sic) 1

Basic Research (BR)--research directed toward the increase of knowledge in science, the primary aim of the investigator being a fuller knowledge or understanding of the subject under study

Development, Test and Evaluation (DT)--projects directed toward the development, test, or evaluationof items of equipment and/or systems for experimentation or operational use

Management and Support (MS)--items of general support, necessary for the management and operation of RDT&E installations or activities

All expenses covered in RDT&E appropriations are classified in one of the eight principal budget activities presented in Chapter 1.

The expanded set of alternatives external to the R&D community requires classification to assign proposals to the appropriate activities. Concurrently with this classification, a very rough evaluation may be made of the potential value and feasibility of the proposals. It will be assumed here that a single clearinghouse will perform the classification and rough evaluation, but the same functions could be performed at a group of clearinghouses, the only difference being that part of the classification would have been completed by the location of the clearinghouses and the manner in which the proposals were solicited.

The clearinghouse must be staffed by naval officers to evaluate the potential military value, and by scientists and engineers from a variety of disciplines to evaluate the type of research or development required and its feasibility. The classification and consolidation of the proposals is the primary function; the evaluation is necessary to support the classification and eliminate those proposals which are obviously unsafe,

would cause larger problems, or would cost more to carry out than they could possibly contribute.

Once the proposals and problems have been determined to warrant investigation, they are evaluated as to the general category of work required: basic and applied research, exploratory development, or engineering and operational systems development. This classification is based on the difference between the current state of the art and the technological requirements of the proposal. It determines whether the proposals come under the cognizance of CNR, CND, or DCNO(D).

The next classification is performed on a subject basis for research proposals, and on a function or problem basis for development proposals. This determines which division of ONR, NMSE, or other office will have direct responsibility for further evaluation of the proposal. The classification process is summarized in Figure 3-3.

The advantage of increased attention to the search for alternatives and the subsequent classification is that it can increase cooperation and mutual support between activities. Parallel development efforts can be identified and the means to control them established. Areas of mutual interest may be pinpointed quickly and easily; for example, unexpected failures in fire control radars and radio receivers may be traced to fluctuations in the ship's electrical supply or to atmospheric disturbances. A single project could replace two or three projects in solving the problem. Problems in hardware design may be reduced to lack of

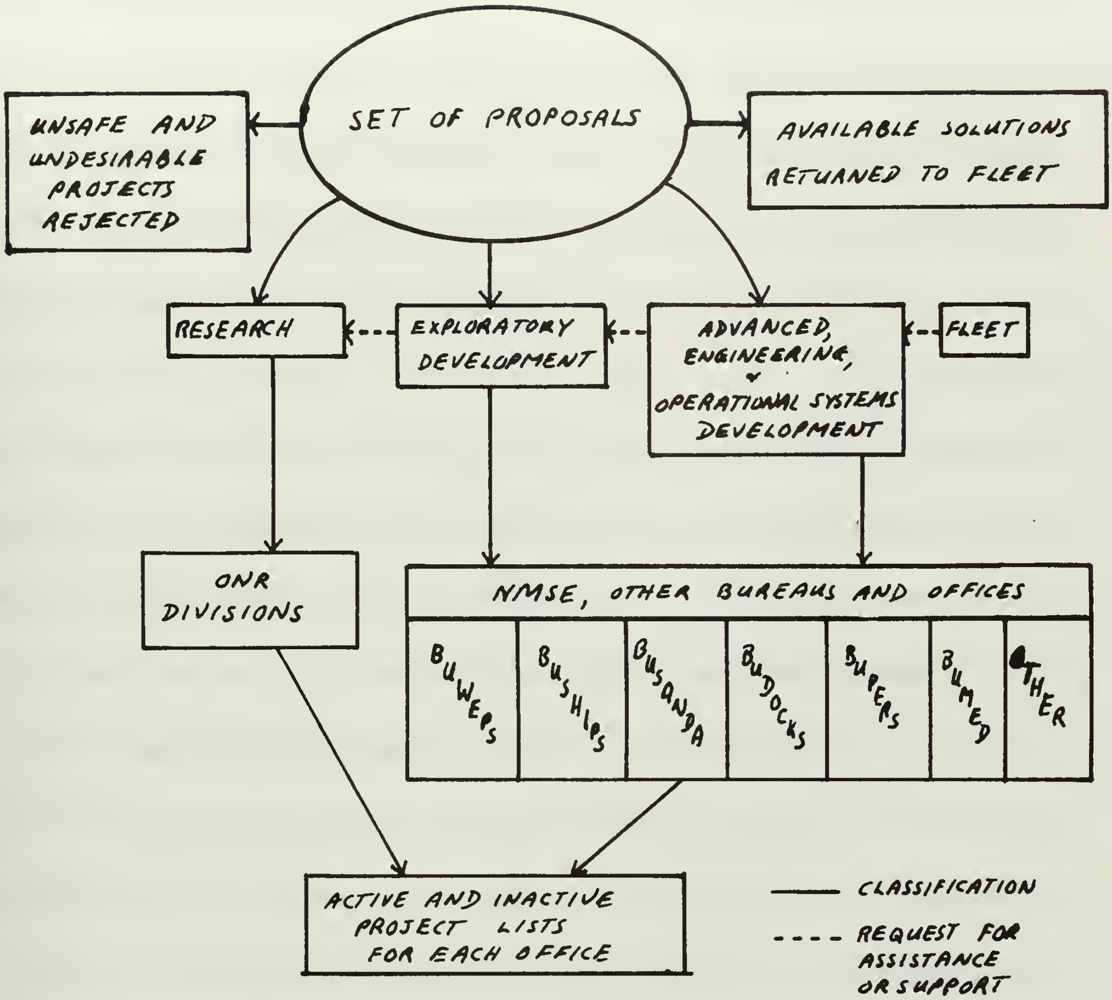


FIGURE 3-3
WORK CLASSIFICATION PROCESS

knowledge of some physical process, and support could be obtained from ONR by the classification system. The solutions to some of the fleet-originated proposals or problems may already be available, permitting off-the-shelf improvements to be accomplished simply by creating an awareness of the problem. Proposals which cut across the classification lines can be readily identified and the necessary communications and cooperation can be established at the outset.

The classification system assists activities in maintaining a list of potential projects which may be undertaken as the current projects are completed, and by permitting early identification of new requirements it may reduce the number of products which become obsolete before they become operational. Proposals which are classified as technologically infeasible become part of an "inactive" list, where they can be re-evaluated as advances in technology and science occur. The appearance of numerous interdependencies may cause projects to be undertaken that separately have little merit and would remain inactive. The maintenance of lists of active and inactive projects has been recommended by Brandenburg and Stedry, and they prescribe in detail the procedures for reviewing the lists.[55] Their presentation was based on a "Research" and "Development" dichotomy, but is applicable to the multiple classification used by the Navy as well.

Implicit in this classification system is the belief that the sequential selection of proposals and the decision on technical approaches to

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[55] B-5, pp 9-15.

be used should be made by the R&D community at the level at which the work must be carried out. The classification system is designed to direct the proposals of those levels, and to provide the working levels with additional guidance on the value of the military applications. By quickly uniting the problems and the personnel trained to solve them, and by early identification of interdependencies, the classification system provides the first step to speeding technological progress, which is a major objective discussed in the next chapter.

Chapter 4. Evaluation of Alternatives.

> More rapid technological advance is possible if there could be a more rapid bringing together of needs, idea sources, and allocable resources in the right kind of environment.[56]

The alternatives arriving at each activity cannot be immediately converted to full scale R&D projects. It is necessary to review the alternatives and acquire additional information about them to decide which ones should be studied in more detail; this process is repeated several times. This chapter discusses the sequential evaluation process as it is currently being carried out and presents some possible modifications.

A highly significant characteristic of the R&D process is its dynamic nature. The proposals and problems are not reviewed, evaluated, and rejected or advanced to the next stage en masse, but instead flow through the system with a large measure of independence. New proposals are taken under study as approved projects are completed or dropped. The progress through the system of individual proposals is presented in Figure 1-11.

For engineering and operational systems development projects, the initial investigation is performed in writing the PTA, or similar proposal for smaller projects. If major problems of development are

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[56] B-60, pp 48. Citing "Management Factors Affecting Research and Exploratory Development," Arthur D. Little Inc., pp II-7.

identifiable in proposals of marginal significance to the Navy's mission, the PTA may be delayed until a supporting research or exploratory development project is completed. Completed PTA's are reviewed by CNO for their potential contribution. If requirements have changed or more desirable means of solving the same problem are available, the proposal will be dropped. The more valuable proposals are examined for the degree of risk involved. If this risk is high, the proposal may be designated as an Advanced Development Project. If the risk is acceptable an SOR is issued and further study is undertaken to produce the Technical Development Plan. At this point the activity formulates plans for carrying the project through to production and operation. The expense of obtaining enough information to develop these plans requires both a high potential military value and a high probability of successful development. The TDP is reviewed by CNO and DDR&E and if approved becomes a full scale project. The procedure is long and tortuous, and only the best proposals survive.

The successive requirements for review contribute to the long R&D lead times and appear to be a departure from the policy of decentralized execution. The question arises as to how much of the review process is designed to keep top management informed and how much is necessary for efficient control. The answer, quoting Secretary of Defense McNamara: "Poor planning, unrealistic schedules, unnecessary design changes and enormous cost increases...have continuously

disrupted the efficient operation of our research and development program,"[57] i.e., under present conditions the review is designed primarily for control. The need for control, and hence the time required for processing the proposals, may be decreased by introducing a more orderly and integrated evaluation process, by improving the project reporting process, and by increasing the emphasis on promulgating objectives and requirements to the R&D community. This is easier said than done, but not impossible. Some suggested approaches are presented in the following pages.

The activity has been provided with a set of problems and proposals, an indication of their military potential, and information concerning interdependencies within the set of proposals and with proposals being investigated at other activities. It also has a list of its own objectives and a knowledge of its facilities, personnel, and current projects. It must combine this information to maximize its contribution over time to the R&D effort, a difficulty quantity to measure after the fact and more difficult to predict. A tentative measure of effectiveness is the expected military potential of completed projects, which is to be maximized subject to cost and resource availability constraints. This topic will be considered in more detail in Chapter 5.

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[57] B-28, pp 1. From a hearing before a subcommittee of the Senate Appropriations Committee on 24 April 1963.

The following information is desirable in solving the allocation problem: the exact characteristics of the anticipated output and its associated military worth; the probability of achieving that output; the cost of achieving it and then producing, operating, or implementing it; the required amount of time, manhours, and other resources; and trade offs involving time, cost, performance, and reliability. It is not possible to obtain this exact information in advance. In fact it is often difficult to obtain much of it even after a product is in use. The managers must settle for a series of estimates, each one a little more detailed and, hopefully, more accurate.

It will be useful for discussion purposes to divide the information gathering and evaluation process into three phases. The first is applicable to all categories of the R&D program, except Operational Systems Development which will be covered separately, and corresponds to the PTA study. The second phase is the more detailed study required for preparation of the TDP, and it is applicable only in a general sense to the Research and Exploratory Development programs. The third phase includes the selection of projects from completed TDP's and the handling of subsequent PCR's; it is the "official" R&D program as included in the FYDP. At this phase, a "clearinghouse" is available in the form of the Navy Department Program Information Center (NDPIC). This Navy office is responsible for processing and correlating requests for new programs and changes to approved programs, maintaining and

updating the documents associated with the FYDP, and monitoring the program for balance and consistency with approved Navy PO.[58]

## Phase I--Initial Investigation.

The alternatives received from the clearinghouse must be reviewed quickly to provide additional correlation of problems and proposals and to select those that can be most efficiently studied as a single project. These related problems and proposals will be referred to as phase I projects. The managers should then assign two or three researchers to conduct the initial investigation of each phase I project. The first step is a clear, concise statement of the problem, and assistance from a Navy representative is desirable for this. The given proposals and the researcher's knowledge of the state-of-the-art must be applied to the problem to estimate the difficulty of obtaining solutions to the problems. This may be a success-or-failure consideration, but the possibility of attaining down-graded objectives or "interim" solutions should also be investigated.[59]

The feasibility of the phase I project is not by itself sufficient to warrant proceeding with development. Once the problem and desired solution are defined and the potential value assigned, estimates must be made of the probability of achieving the solution by each of the feasible approaches (or the best approach is one is obvious). Similar

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[58] B-18, pp 3-6.

[59] A-11, pp 130.

estimates must be made of the R&D cost, system cost, personnel requirements, time needed to achieve the solution (not the "crash" schedule unless the problem is desperate; the time-saving benefits of a crash program are highly questionable) and product reliability. Trade-off analyses are also required for the PTA; a value-engineering approach is useful even in the initial design and planning stages. By providing an estimate of the requirements and schedule for attaining both the desired capability and degraded objectives, the phase I study group puts the trade-off information in the most useful form for the activity manager.

Some of the projects may require a major advance in the state-of-the-art, and the advance may require work not usually done by the activity. Such projects may be transferred (completely or in part) to the Research or Exploratory Development categories, or recommended for contractor performance. A phase I project may be in good shape except for a particular portion, and that portion may warrant Exploratory Development support or closer attention as an Advanced Development project. Any transfer of responsibility should be accompanied by the report of the phase I project findings, including the reason for trasnfer. The process of combining related problems and proposals may eliminate the basis for some entirely.

It is emphasized that phase I is envisioned as a thoughtful, systematic, and rapid first cut at project evaluation. The actual number of man-hours required will vary with the complexity and magnitude of the

problem addressed, but to indicate the level of effort proposed, three-quarters of the projects should require less than six research man-hours. This number is considerably less than the current level of effort applied to the PTA (activities are now required to submit PTA's within 90 days of the issue of the GOR or TSOR[60]), but it is assumed that the report will be utilized at the activity level for preliminary planning rather than being forwarded to CNO. The large number of alternatives which must be considered necessitates this rapid evaluation.

In order to implement this rapid initial evaluation procedure, there are three essential requirements: (1) a personnel assignment policy which permits a small percentage of the activity's research personnel to concentrate on a review of recent developments in their field and to work on the initial evaluation, (2) a set of estimating relationships for the required information, and (3) the accurate and detailed information of Navy R&D objectives emphasized in previous chapters. The evaluating personnel would not be assigned on a permanent basis; it may be convenient to assign scientists and engineers to evaluating duties as they complete current projects. This would provide them with the opportunity to catch up on the literature, investigate new problems, request projects for their next assignment, and gain a better appreciation of the manager's problems as they assist him in the planning process.

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[60] C-14, pp 4.

The estimating relationships will require pre-implementation and continuing analysis. Many estimating relationships are now available within the activities. CNA and other organizations performing cost analysis have developed additional data and estimating techniques. The Navy Program Factors Manual contains some cost information that may be used directly. Rapid costing techniques which would be useful for this phase are presented by A. J. Meltsner in reference B-39. Other estimates may be derived from available data; some will require educated guesses and provision for the collection of new data in the future. The time allotted may seem to deny the existence of the uncertainty. On the contrary, it gives full recognition to the fact that initial estimates have generally been inaccurate.[62] Reliance on detail at this stage cannot overcome the inaccuracy. The additional time and effort required is difficult to justify. The belief that smaller errors in a large number of components will provide mutual cancellation has not been substantiated in practice.

The procedures of phase I are consistent with the concept of decentralized execution supported by promulgation of specific objectives and requirements, with the benefits of bringing research personnel into the planning function, with the requirements of researchers for time to keep up-to-date in their field, and with accelerating the advance of technology as indicated in the quotation beginning the chapter. The procedures are not consistent with the current requirement for CNO

[62] B-37, pp 1.

review of the PTA, but the phase I reports should be adequate to keep top management informed. The measure of uncertainty makes the advantages of top-level review at this stage questionable. The activity manager and his "evaluating teams" are in a better position to weigh the uncertainty. Forwarding the phase I reports of only those projects scheduled by the activity manager may be sufficient; it may be a closer approximation to what is actually being done than is apparent from the formal procedures described in Chapter 1. Possible format and contents of the phase I report are indicated in Figure 4-1.

Implementation of these procedures would be difficult but justifiable. In addition to the advantages listed above, it would contribute to building the much needed data base, especially for early estimating relationships. "Keeping score" of the accuracy of the estimates would improve the estimates. The difficulty of having the people with the right skills available to do the evaluating should be controlled by the classification process and the personnel assignment policy. (The inter-subject communications could easily improve to the point where many problems could be resolved during a coffee-break or stock-market review.) The procedures will facilitate early recognition of major problems, permitting an early start on critical areas.

Phase II--Detailed Evaluation.

The second phase requires that the steps of solving the problem be spelled out in detail. The funds, resources, and personnel

Figure 4-1
Phase I Report

Activity: Project Classification: Proposal Source:

Prepared by: Phone: Date: Title:

Statement of problem:

Proposed solutions:
A.
B.
.
.
.

Evaluation:
A.
B.
.
.
.

Requirements/characteristics:

| Proposal | R&D cost | Total cost | Total personnel desired/required | Phase I personnel | Time to completion | P{success} | Product reliability | Potential value |
|---|---|---|---|---|---|---|---|---|
| A. 1. | | | | | | | | |
| 2. | | | | | | | | |
| B. | | | | | | | | |
| C. 1. | | | | | | | | |
| 2. | | | | | | | | |
| . | | | | | | | | |
| . | | | | | | | | |
| . | | | | | | | | |

Recommendation:

Critical problems: Support requested:

Remarks:

requirements must be estimated as accurately as possible. The problem of whether to conduct the research in-house or to contract for it must be considered. The specific information required in the TDP is listed on page 47, Chapter 1.

Phase II would normally require a slightly larger number of researchers, perhaps three to five, depending on the size of the project. The study is sufficiently detailed to identify the major problems which may be added tothe list of alternatives at other activities or selected for pursuit as separate projects within the evaluating activity. It has been recommended that definite criteria be established for transfer of work between various categories of R&D,[63] but the difficulty of making standardized measurement of research and development progress or problems points to the telephone as a more reasonable means for deciding whether or not to make the transfer.

As the alternate approaches to solution are worked out and displayed on a PERT diagram (one of the TDP requirements), more detailed cost estimates are possible. Engineering estimates and research experience can be brought to bear in addition to statistical techniques. Institutions such as RAND rely heavily on the latter, but they do so largely because they cannot keep on their staff the great variety of engineering skills that would be necessary.[64] But if the activities perform their own cost estimating for routine projects,

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[63] A-7, pp 78.

[64] B-34, pp XIII-1.

they can benefit from the engineering estimates as well. To the extent that it may be a deviation from current practices, the concept of the activities performing their own estimates should be emphasized. The information to be obtained is essential to conducting projects. Even if it is never written down, it enters into project selection consideration. The estimating techniques are not such abstract or specialized procedures that economists or reliability engineers or value-engineering specialists are required, although such assistance should be available for unusual cases. In using the PERT diagram or similar representation of project effort, the timing of estimated expenditures can easily be obtained. While the total expenditures are required, the cost-by-time information should not be omitted from the presentation since the manager will have a preference for both the time and amount of expenditures.

Mentioning cost and time together brings up the subject of discounting or time preference for expenditures. There are a number of widely used discounting techniques, and arguments have been made against the use of any of them. It is not the purpose of this thesis to resolve the discounting question. The use of discounting to account for risk, however, is specifically opposed. The risk can be better controlled by evaluating the project's probabilities of success, and by administrative procedures such as the use of Advanced Development projects rather than Engineering or Operational System Development projects. Broussalian argues the time preference discounting can be applied

only to marketable streams.[65] It is not reasonable to place military capabilities in that category. Furthermore, the different capabilities sought cannot generally be assumed to behave according to the same time preferences.[66] It is more reasonable to incorporate time preferences in the project definitions by altering the potential military value of the objective obtained at different times. This approach can better reflect urgency as determined by battlefield requirements or SECDEF decree. It is probable that when these considerations apply, they will often be overriding; i.e., if a new anti-SAM weapon system is required for immediate use in Vietnam, that research will probably be started without detailed comparison with all other current and proposed projects. Lesser degrees of urgency may be handled by modifying the value of objective as suggested.

It is proposed in the next chapter that the expected budgets for successive years be used to constrain R&D expenditures. The discounting techniques imply alternative use of funds, such as putting the money in the bank. Such lending and borrowing concepts are poorly defined within military budgeting concepts. The discounting techniques introduce a preference for future expenditures over current ones; this tends to further reduce cost estimates which have traditionally been too low. While the underestimation cannot be blamed on discounting, discounting techniques exaggerate a recurrent error. Similar

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[65] B-7, pp 1-6.

[66] Ibid.

reasoning applies to discounting future benefits, since "a pervasive tendency to undervalue future outputs relative to current ones"[67] already exists. And finally, the errors in estimates are apt to obscure the refinement supplied by discounting. For these reasons, discounting will be omitted. Again, it is not the purpose of this discussion to permanently rule out discounting. It may be reintroduced in the model if desired.

The TDP includes estimates of production, operating, and maintenance costs. This information is primarily for top-management review. The estimates of the timing of these costs are apt to be less accurate than the estimates of the R&D costs and timing. Estimates of total expenditures for these categories, estimates of the time of starting production and operation, and a brief outline of the transition from research and development to production, training, and operation should be included. However, the effort required for great detail in these areas at this phase is again difficult to justify. Reasonable estimates are important in deciding which projects to select and which completed projects to produce, but the high project mortality rate can lead to much wasted effort. As the projects progress, more reliable estimates become available and more accurate planning is practicable.[68] When to expend effort to obtain information is another managerial consideration.

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[67] A-8, pp 248 and Chapter 2.

[68] A-14, pp XV, 17.

Cost distributions are more helpful than point estimates in recognizing the degree of uncertainty in predicting costs, although they make computations more difficult. The distributions give managers a better picture of the possible outcomes of their plans, and make them painfully aware of the flexibility that their job requires. Dienemann and Sobel[69] have suggested interesting techniques for combining the distributions to predict total costs. Both techniques obtain beta distributions based on estimates supplied by the activity for each of the uncertain cost factors. Dienemann's model combines the cost distributions by Monte Carlo techniques to obtain the total cost distribution. Soebel's model employes the first four moments of the beta distribution to obtain the total cost distribution. Both procedures have been computerized; Dienemann's is easily applied only if the costs of inputs are independent. Except in large projects, the expected value approach is sufficiently easier to make it preferable, and the intuitive notion of the uncertainty involved is adequate.

As the phase II study progresses, it is important to acquire a source of military information and a review of related studies which have been completed or are in progress. As alternate development paths and trade offs between performance and cost of development appear, information on the operating environment and requirements becomes critical. The fleet input to the set of R&D alternatives may provide some sources, and P-coded officers on sea duty could serve

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[69] B-20, and B-57, respectively.

as fleet R&D representatives as a "collateral duty." Any such use of the training supplied by the Navy warrants consideration, and in my personal opinion, the extra challenge would be appreciated and not resented by the P-coded officers. The review of related studies may reveal immediate solutions, sources of additional information, and some major problems, and it should eliminate unnecessary duplication.

All estimates in the TDP should be documented to show which costs and problems were considered and which techniques were used to obtain the estimates. Changes in product concept or specifications must be clearly identified in time, the new estimates explained, and the old ones retained. Historically these changes have been a major reason for poor estimates and for the difficulty of obtaining valid information from old data.[70] This information is essential to the activities in improving future estimates and techniques, and it may also permit subsequent review to detect errors of omission. Specific identification must be made of areas of uncertainty. If the project is approved, the uncertainties may be eliminated at various stages of development. If the uncertainties are clearly pointed out in the TDP, the process of updating estimates and plans is much easier than if the uncertainties are sprinkled liberally throughout the document or enter only as generalized "safety factors." L. S. Hill has addressed this problem in some detail and presents the following checklist for

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[70] B-31, pp 50.

estimating uncertainty:[71] state-of-the-art, capability and availability of personnel, test results, availability of hardware, system reliability, interfaces with other projects, and anticipated impasses or breakthroughs.

In phases I and II, standardized estimating techniques and documentation of the procedures, sources, and considerations have been emphasized. If followed up by a cold, clear evaluation, they may help eliminate Perry's "mythography"--a term which "identifies a situation in which an unreal representation of events and their causation becomes widely acceptable and is eventually transcribed into a procedural ritual."[72] In a rather caustic but healthy examination of military R&D, he points out several examples of such occurrences. One example of particular interest to R&D managers is that of program acceleration, which Perry indicates may have been made an unrealistic option by today's "extremely tight but inherently realistic scheduling."[73] He compared ten similar Air Force programs, five of which were conducted at the "normal" rate and five as "crash" programs, and found little difference in the average times between the groups and less variance within the group of accelerated projects. While the evidence is not overwhelming, it does warrant second thoughts about the employment of crash programs and the disturbance they cause in the rest of the activity's effort.

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[71] B-29, pp 6-8.

[72] B-47, pp 2.

[73] _Ibid._, pp 5-8.

Early estimates of reliability are also considered by the phase II study group, and steps are spelled out for testing to be performed and requirements which must be met. The reliability procedures for weapons systems are highly refined and very demanding.[74] They are so extensive that it appears that there may not always be enough time and people available to perform all the required tests. This would result in final tests being administered on a sample of the prescribed tests. Somewhat less attention is devoted to the cost and time trade offs associated with acquiring the reliability estimates and confidence intervals. The lack of flexibility is justifiable in cases where the reliability determines the safety of personnel, but where reliability is not so vital it may be advantageous to permit and encourage a value-analysis approach to reliability requirements.[75] Use of the exponential distribution and the "no wear-out" assumption in many tests adds to the conservative nature of the reliability program. While increased flexibility is desirable, the overall reliability program and its execution provide an excellent model for developing other estimating techniques. Cost, time, and probability of success are more difficult to estimate, and there are no tests of these quantities similar to reliability tests, but an attempt to include these factors with standardized procedures must be made.

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[74] See references B-26 and B-52.

[75] B-55, pp 1-9; B-22.

Phase III--Evaluation of Projects in Process.

Phase III commences when the project is approved for inclusion in the FYDP and the actual research and development is started. The evaluation of trade offs, problems, and progress must continue until the project is completed or dropped. The same considerations presented in the first two phases are applicable, recognizing that decisions are being reached at various stages. Phase III will be discussed in Chapters 6 and 7.

In-house or Contracting Decisions.

The proposal evaluation process is designed to provide managers with the information required to make decisions onthe selection, scheduling, and control of projects, and to combine with the reporting process to permit a thorough examination of completed and cancelled projects. One of the decisions that must be made is whether the work is to be conducted in-house or under contract with industry or non-profit R&D institutions, and if the work is to be contracted, how is the contractor to be selected? This is itself a complex problem and much has been written about it. Only the type and availability of information recommended as a basis for this decision are considered here.

The first step is to determine whether the Navy has the capability to carry out the project. Indications of the answer to this should develop early in phase II as the procedures for development are outlined, but the study group must have a working knowledge of the Navy's

facilities and the research personnel assigned to perceive the indications. It may be better to leave the evaluation to the activity manager on the basis of the study group's project description. On the other hand, requiring the study group to be familiar with the capabilities of other Navy R&D activities will encourage communications and increase cooperation among the activities. This appears to be one of the least expensive ways of combating the difficulties presented by extensive decentralization.

If the proposed project is within the Navy's capabilities, the Navy will usually conduct the R&D. The Army, which has a more centralized R&D organization than the Navy, points out the following advantages of the "in-house" capability:[76]

(1) the availability of technically proficient personnel helps to keep the contractors honest
(2) the service laboratories are closely tied to the associated military capabilities or branches
(3) knowledge of military requirements is better
(4) the in-house capability permits better control over project and program continuity
(5) distinct lines of authority and control are provided
(6) recognized and controlled competition and duplication are maintained
(7) funds are available for study of subjects of doubtful interest to industry and university research

Even when the Navy capability exists, one of the manager's scheduling options is to contract some work to smooth the program workload and reduce costly and difficult hiring and firing.

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[76] B-62, pp 15-16.

If it has been determined that the Navy does not have a particular capability, the next question is, should the capability be acquired? Generally it will not be feasible, but it should be given consideration when a new field is developing and/or when a new and continuing military requirement becomes apparent. The expected costs of renting the services or developing the capability must be estimated, and the results discussed with CNR, who is responsible for advising ASN (R&D) on matters regarding modification of the Navy's R&D facilities.

When it is decided to have the work done under contract, then the contractor must be selected. For the larger projects the decision is reached through competitive bidding. But a substantial number of R&D contracts are negotiated non-competitively with a single firm. Many of these contracts result from industry's interest in Navy projects and their willingness to undertake some of the preliminary research at their own expense in hopes of getting the inside track on later projects.[77] Again, it is to the Navy's advantage to encourage this activity, and to do so openly to stimulate competition.

Numerous criteria have been suggested for use in contractor or source selection; most of them are subjective, or at best, difficult to measure. Others have attempted direct quantification by the number of published papers, patents, and PhD's, but these don't directly measure the potential military contribution. Evaluation of past performance based on whether delivered items exceeded, equalled, or

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[77] A-14, pp 83; A-18, pp 335.

fell short of specifications is a more pertinent measure, and a similar evaluation of costs and time schedules should be made. This analysis is compounded by the project changes that occur so frequently.[78] The subjective estimates of performance can be improved by more careful recording of all changes to project estimates as suggested previously.

The Concept Formulation/Contract Definition procedures (see Chapter 1, pp 47-8) were established for major projects as a result of the following problems:

(1) failure to achieve the desired effectiveness
(2) large cost overruns
(3) project cancellation after much time and heavy expenditures
(4) descriptive changes, caused by overdependence on technological breakthroughs

When the CF/CD procedures were implemented, several difficulties were encountered. These difficulties were studied for DoD and summarized in <u>Lessons Learned from Contract Definition</u>[79] and are discussed in the next three paragraphs.

Lack of government guidance in the CD Work Statement reflected directly in the contractor's efforts. The need for describing requirements in the early stages of the project is even more important in dealing with contractors than it is in the in-house work, because the contractors will have less knowledge of the Navy's objectives and problems. The government should include in its guidance the trade offs

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[78] B-40, pp 5.

[79] Reference B-13.

which are to be considered and the ranges over which the trade offs are acceptable. The report recommended that the contractors be allowed freedom in making the trade-off decision, but this is heavily dependent on the government's ability to make the difficult specification of limits in advance. The military services will not want, and cannot afford, to relinquish these decisions. If the decisions were left to the contractors, the services would probably reduce the trade-off ranges to a "$\delta$-neighborhood" about the desired quantity, and the system would be right back where it was before trade-off analyses were introduced.

Two particularly delicate areas of Contract Definition are subcontracting procedures and the government requirement for unlimited data and design rights. The report indicates that both require additional funding and study. In selecting the contractor, management must consider whether the bidder will be making use of his technological strength or is attempting to establish himself in a new field. The quality of the planning in the Contract Definition phase is weighed heavily by the government in source selection, and as a result, contractor planning and R&D costs have increased. It may be reasonable to consider giving R&D contractors "secondary data rights" which would limit transfer of R&D results to source contractor's competitors, or attach an additional cost to such transfers. Contract incentives could be related to these secondary rights.

The major difficulty in CD was identified as the excessive delays in initiating actual development which resulted. The causes for the delay were listed as:[80]

(1) insufficient evidence that prerequisites would be met
(2) lack of specified minimum acceptable requirements
(3) extra time required for evaluation of contractor/ subcontractor proposals
(4) slowness of decision in OSD, and administrative delays in the services.

Throughout this chapter the problem of obtaining detailed information before work commences has been emphasized. The delays from contract definition are excellent examples. The realistic use of trade offs as recommended will help solve the dilemma, but the best answer lies in developing a means of writing good faith and cooperation into a legal contract. These are the only ingredients that will bring about significant reduction of the delays. The uncertainties and risks of R&D demand that the sequential decision-making process be incorporated in the contract. Neither government nor contractors will want to absorb all the risk. The solution will probably involve sharing the risk and the efforts to reduce risk by improving estimating procedures. A Summary of Lessons Learned from Air Force Management Surveys[81] gives added support to these conclusions, and it is another publication of interest to Navy R&D managers. It is more detailed than the CD report, and is not restricted to CD; it is a concise presentation of problem symptoms and causes, and corrective action taken.

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[80] Ibid, pp 18.

[81] Reference B-1.

Parallel Development.

Parallel development in R&D is another subject that has been presented in this chapter, although it has not been identified as such. Parallel development is a process of controlled duplication in which two or more means of obtaining a given objective are pursued. Exploration of multiple alternatives has been a primary consideration in both Chapters 3 and 4, and the process should continue at least until success along one path is assured. Hitch and McKean present the criteria for the amount of duplication as follows:[82]

(1) the greater the expected payoff from the research, the greater the duplication
(2) the greater the uncertainties involved, the greater the duplication
(3) the cheaper it is to duplicate, the greater the duplication
(4) the greater the qualitative differences in alternatives, and the greater the degree of independence of factors determining success, the greater the duplication

For these and any other criteria that may be developed, it is essential that the amount of duplication be known and controlled. The clearinghouse concept, the classification process, and the sequential evaluation process are all specifically designed to provide the required information and control, and to exploit the advantages of parallel development.

R. R. Nelson presents an interesting case for parallel development[83] and stresses the sequential nature of collecting information.

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[82] A-8, pp 249-251.

[83] Reference B-43.

He concludes that when estimates are unreliable, the best decision is likely to involve obtaining more information--through development--about alternative proposals.

Evaluation Differences by R&D Category.

The sequential evaluation and decision-making concepts discussed in this chapter are applicable to all categories of R&D. Hence, all categories were treated together. This does not imply that no distinctions between categories are acknowledged. The greatest differences lie in the extent to which estimates are possible and in the complexity of the objectives. (Complexity here refers to the number of components and interfaces involved in the desired end result, not the difficulty or sophistication of techniques involved.)

In Research, the manager's only objective is to advance the frontiers of knowledge in some area of possible interest to the Navy; these areas are not restrictive. More than in any other category, efforts in research require a certain amount of faith in the scientific process. It is interesting to note the frequency with which this high evaluation of the capabilities and advantages of basic research is advocated in the literature. The Navy apparently has more of this faith than the other services. (See Appendix A.) In 1959, the Naval Research Advisory Committee recommended to the Secretary of the Navy that a fixed (and increased) percentage of the total R&D budget

be allocated to basic research.[84] This is a rather arbitrary way of running an R&D program, but there are no adequate measurements of the return on R&D to develop more refined techniques. Apparently until better methods than those given in the introduction of Chapter 9 are developed, we shall have to keep the faith. Incidentally, the Navy's Research expenditures in 1964, 5, and 6 were approximately 9.7%, 9.3% and 9.8%, respectively, of its total Program VI expenditures.

A review of the research/development percentages of total R&D expenditures and company net annual sales failed to provide guidelines as to what the percentages should be. The definitions of the two categories varied from firm to firm, and the data were not available at all for some companies. The amounts and percentages varied widely with the type and "age" of the company and with its speciality area.[85] The report by the Naval Research Advisory Committee discussed above suggested as a general rule that the emphasis on basic research should increase with the technological strength of the enemy and decrease as the immediate probability of conflict increases. They further recommended that the detailed allocation of effort be made by division managers with the advice of competent scientists,

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[84] Reference B-42.

[85] B-58, Part II.

placing their bets on the basis of the competence of the investigator and the relevance of the project.[86]

Exploratory Development is directed toward somewhat more specific objectives, but not generally to the point of detailed a priori specifications of end-item characteristics. In seeking potential applications of advances obtained from the Research category, or external breakthroughs, this category demonstrates the direction of information flow from pure science to operational military products. The combined system flows are presented in Figure 4-2. Frequently a great deal of testing and experimentation is necessary before specific applications can be formulated. This requires that the phase II type of evaluation be accompanied or preceded by testing and experimentation. Estimates of military potential become more meaningful in allocation of effort.

Advanced Development projects involve an intensified continuation of Exploratory Development or an additional stage of evaluation for Engineering Development or Operational Systems Development projects involving high risks. Glennan[87] describes projects in this category as the building blocks from which operational products are developed, and recommends greater utilization of this category. As key areas in funding, the Advanced Development projects give full recognition to

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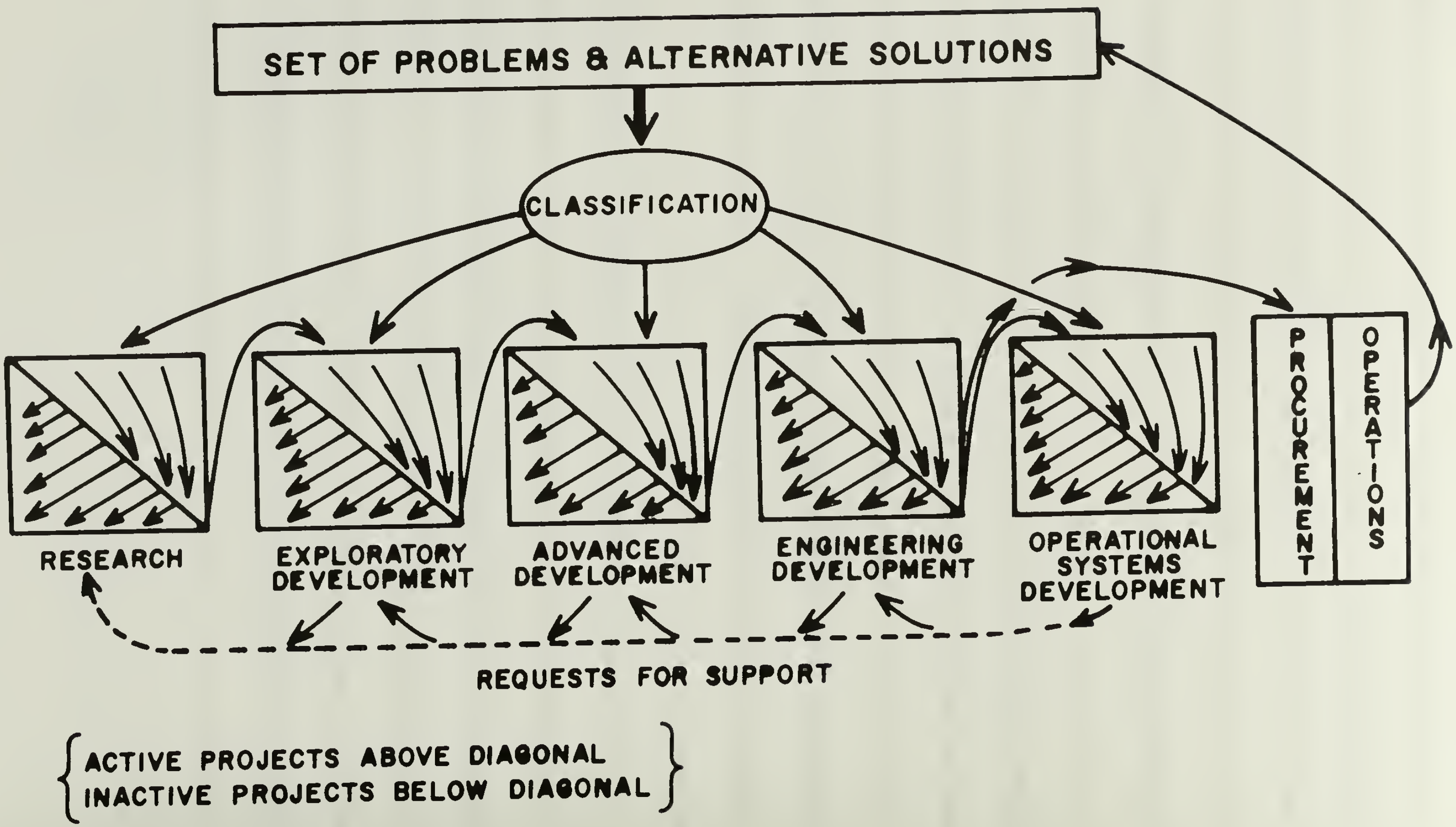
[86] B-42, pp 5, 53.

[87] B-25, pp 7, 16, 26.

FIG. 4-2 INFORMATION FLOW



the sequential nature of R&D planning. But if they must meet the same requirements for approval as Engineering or Operational Systems Development, the procedure will be self-defeating and will lead to relative short-range projects rather than the more sophisticated, technologically advanced development for which they were designed. Glennan suggests that the Advanced Development projects should be applied to components, drawing the components together only when the threat or need becomes more clear.[88] The potential advantage is more rapid administrative processing of the proposals, but the suggestion must be implemented with caution. A common criticism of R&D efforts is that excessive delays occur in integrating system components to obtain compatibility. If the necessary coordination can be supplied informally, then the suggestion can be made to work; without the coordination, the delay will merely be postponed and magnified by incompatibility.

The phase I and II presentations are directly applicable to projects in the Engineering Development category.

Operational Systems Development projects are similar to the Engineering Development category, but differ in that they are more complex and seldom have the same inauspicious beginning. Usually resulting from a threat modification, a major technological advance, or serious doubts about the effectiveness of a current capability,

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[88] Ibid.

these projects are initiated by a detailed systems analysis. The Naval Warfare Analysis Group of CNA performs many of these studies; others are performed by independent systems-analysis groups under Navy contract. The studies do not simply start with a problem and set of alternatives, but instead go back to the preliminary planning phase described in Chapter 3.

A scenario is developed for the problem under consideration, and measures of cost and effectiveness are considered for evaluating alternative means of meeting the specified commitment. The alternatives are postulated from existing forces and capabilities and from recent or anticipated technological advances. These inputs are combined in a mathematical (optimization) program, frequently computerized, and the alternatives are evaluated by the program. The study and results are recorded in a report for management evaluation; the report usually fills several volumes and often requires a summary report. Management's decisions are then implemented as Operational Systems Development projects. Phases I and II have been completed, and phase III commences with a reduced set of alternatives--often only one. Parallel development generally receives little or no consideration. Dissenting opinions in the analysis are often deleted from the report in interest of preserving the activity's image.

The procedure is impressive and very useful. But it is so impressive that it may suppress questioning and doubts, and therein lies the danger. So, let the procedure be examined for elements of mythography.

To consider the obvious first, the model can be no more realistic than the assumptions that are built into it. The assumptions must be clearly stated, collected for easy review, and evaluated for their effect on the results. Is the scenario reasonable? If not, the alternatives can be evaluated under alternative conditions, and this is often done. Are significant alternatives omitted? If so, additional computations can be made quite easily. Are trade offs considered? They usually are, and if the report is not filed away in a dark closet, the trade offs can be very helpful in continuing project analysis throughout the development process. The comparison of alternatives is likewise useful, and can be a major asset in considering parallel development--if the alternatives have not been ruled out on the basis of the initial evaluation. Once again, the importance of recognizing the uncertainties in the development of postulated alternatives is obvious.

The question of what happens to completed studies is recurrent in the preceding paragraph. The final study report can be invaluable to the activity performing the project R&D if it is available, utilized, and clearly written. The analysis should not be considered as a one-shot, self-destroying process. The clarity of the report is even more critical to the reviewing authorities. In studying a number of final reports, that element was found to be absent in some; its absence was dramatized in cases where the resulting summary report failed to give a faithful reproduction of the actual conclusions of the study.

The summary report is usually written when the full study report is too lengthy to permit efficient review by management. This implies the decisions are to be made on the basis of the summary report. This in turn implies that when the summary report distorts or misrepresents the conclusions, there will be a direct waste of several man-years of effort in systems analysis, a greater waste in subsequent R&D and procurement, and--if the errors are not discovered--a major decrease in the potential efficiency of the operational system.

Discussion of this specialized version of phases I and II leads to the conclusion that the systems analysis should be:

(1) carefully and thoroughly developed
(2) clearly presented (and accurately summarized)
(3) critically evaluated by management, and
(4) consulted in subsequent project phases to cope with uncertainty

Chapter 4 has emphasized the dynamic nature of R&D, the manner in which information available increases with stage of evaluation, and the need for a sequential decision process. And it has casually slipped over the difficult problem of how the selections are to be made, but that topic can no longer be postponed.

## Chapter 5. Sequential Selection of Projects

> Frequently the problem of achieving efficiency in the entire collection of R&D projects has been ignored. It is assumed that a collection of projects each of which is efficiently run will lead to efficient achievement of the total R&D objectives.[89]

The opinion expressed in the opening quotation could be derived from a casual observation of most R&D operations. The varied assortment of projects and the random appearance of the means of selecting them stem not from a lack of concern for the efficiency of the overall program, but rather from a lack of quantitative methodology for research planning.[90] The primary causes of this condition are the multiple sources of uncertainty which inhibit the direct application of techniques used in other areas, and the fact that the R&D process is designed to upset the equilibrium conditions upon which most economic models are based. This chapter discusses the problems of project selection and some of the proposed solutions.

Specific selection criteria and the availability of information from the evaluation process open the discussion and are followed by broader considerations of program balance. Some possible measures of effectiveness and constraints are presented and a selection model

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[89] B-25, pp 2.

[90] B-54, pp iv.

is developed. A representative group of optimization techniques is reviewed. Chapters 7 and 8 present possible methods of obtaining more refined techniques.

Much of the Navy's R&D effort is directed at developing new products. Other important considerations are modifications to existing equipment or revisions of operating techniques to reduce cost or increase effectiveness or safety. The operating techniques are studied by the Operations Evaluation Group (OEG) of CNA, and its efforts are generally separated from the rest of the R&D community. But the observations they make on forces and equipment in action provide valuable information for the R&D process. Not only do indications of equipment problems become apparent, but the development of new tactics or operating procedures may provide additional insight into design characteristics and specifications for future equipment. These observations increase the data base for the evaluation process, and the study performed provides a potential means for measuring the effectiveness of completed R&D projects. The different purposes of R&D activities must be considered in the selection process and full advantage taken of the additional information available from the fringes of the R&D community.

Selection Criteria and Availability of Information.

The clearinghouse classification process is basically a rejection process. Proposals are reviewed for military desirability and safety,

and those found lacking in either are eliminated from the program. A few proposals may be rejected on technological grounds. Some techniques may have been proven unsatisfactory, but current feasibility is used primarily to determine the R&D category to which the proposal should be assigned. If any doubt about a project exists, it should be forwarded.

Phase I continues this process, adds initial cost estimates, and further correlates related topics and proposals. The initial comparison of alternatives eliminates obviously inferior proposals, and other projects which are expected to cost more than they could contribute are rejected. The expected return must exceed the expected cost, but this is a necessary condition and not a sufficient condition for undertaking the project. It is of limited use because the military value is difficult to assess in dollars, but a subjective comparison is useful for forwarding projects to phase II or rejecting them. (The reaction to a PTA recommending "don't do it" is difficult to predict, but "don't" should be included in the set of alternatives.) Even in the case where the military potential and expense of a new product are commensurable, this criteria cannot be used with precision because of the rough estimates used.

The classification review and phase I evaluation thus weed out a relatively small portion of the proposals and group the others so as to identify related problems, alternative solutions, and relationships to projects already underway. More detailed criteria are needed to

decide which projects are to be studied in phase II, pursued as official R&D projects, or dropped from the program, and to decide when these events should occur. The criteria have been discussed in Chapter 4. They will be reviewed briefly here, and some more general criteria problems will be considered.

The literature abounds with lists of criteria which effect project selection; some are easily quantified, others are highly subjective, and almost all are interrelated. Of those useful for military R&D selection (excluding commercial criteria such as expected sales), the following are listed:

(1) potential military worth
(2) state-of-the art; current and required
(3) probability that various alternative solutions will be successful
(4) cost required to perform the R&D
(5) cost required to procure, operate, maintain, and support the end item
(6) time required for R&D
(7) time required for procurement and operation
(8) expected lifetime of product type
(9) reliability of product in mission environment
(10) facilities required for RDT&E
(11) personnel required for RDT&E
(12) project value interrelationships
(13) sequence of dependent projects
(14) cost, time, reliability, and probability-of-success trade offs
(15) previous experience in field

The degree of availability of this information varies with R&D category and the length of time the project has been under study.

The potential military worth of projects and combinations of projects is one of the most important criteria. Assigning relative importance values to independent projects may be accomplished without too much difficulty, but placing even a relative weight on the incremental value resulting from a combination of projects (e.g., manned bombers and ICBM's, as mentioned previously) requires careful evaluation and top-level review. A subjective attempt to include the interdependencies is preferable to omitting them. In projects whose purpose is to reduce the cost of a current operation or procedure, the benefit may be taken as the expected cost reduction. But this raises the incommensurability problem again; the units of military worth must be converted to dollars or the cost savings to units of military worth.

The state-of-the-art consideration may be absorbed in cost, time, and probability of success criteria, but a direct statement of the dependence on technological breakthroughs facilitates updating estimates as the breakthroughs are achieved. The past experience of the activity in a given field requires an evaluation of the capability of the activity to perform a particular type of work and may permit recognition of areas which could be or are being handled more economically by another activity or contractor.[91]

The cost and time estimates were covered in Chapter 4, with the exception of the end item's period of usefulness. The length of

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[91] A-10, pp 33.

time expected between the operational date of the product and the time that it is phased out (by replacement equipment or changing requirements) is useful information, but difficult to predict. In spite of the difficulty, the replacement problem should be specifically addressed. The classification process should ease the burden somewhat by providing an in-flow of related problems and proposals. Direct evaluation of this problem may help award selection of projects which will become obsolete before they become operational, as happened to the Snark and Navaho missiles. Both were overtaken by the IBM program and cancelled before any useful operational capability was achieved.[92]

The timing of projects must be spelled out in detail, and combined with requirements for personnel and facilities. Time interdependence of projects must also be specified. The military value of projects is also time dependent, and this provides the major time preference considerations. The model as written distinguishes between the length of projects, but not between projects of the same duration and different completion times. The dynamic nature of the R&D program makes personnel and facility constraints binding on the selection and scheduling problem. Even if activity expansion is desirable, the acquisition of new facilities will generally require very long leadtimes, and obtaining additional qualified scientists and engineers may also present problems. It is for these reasons that the model constraints

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[92] B-25, pp 15.

developed in the last section of this chapter are expressed specifically in terms of personnel and facilities.

Two probability statements are included in the list of criteria: the probability that a particular technological approach and combination of personnel, time, and funds will successfully achieve the prescribed end product, and the probability that the end product will still be operating at the completion of its designed mission (reliability). The first is a subjective evaluation--hopefully one that will improve with experience in making the estimate--and without entering into the debate on the true nature of probabilities, it does provide useful information. The reliability estimate can be obtained mathematically. If testing can be performed it can usually be specified to any degree of accuracy and statistical confidence. The two probabilities are very much interdependent.

An example will indicate the number of alternatives which rapidly develop from these considerations, even in obtaining a single end item. Consider the development of a hypothetical electrical device, which may consist of tubes or solid state components. Each approach is restricted to only two combinations of personnel and time, and two cost requirements to obtain two different levels of reliability. This results in the following alternatives:

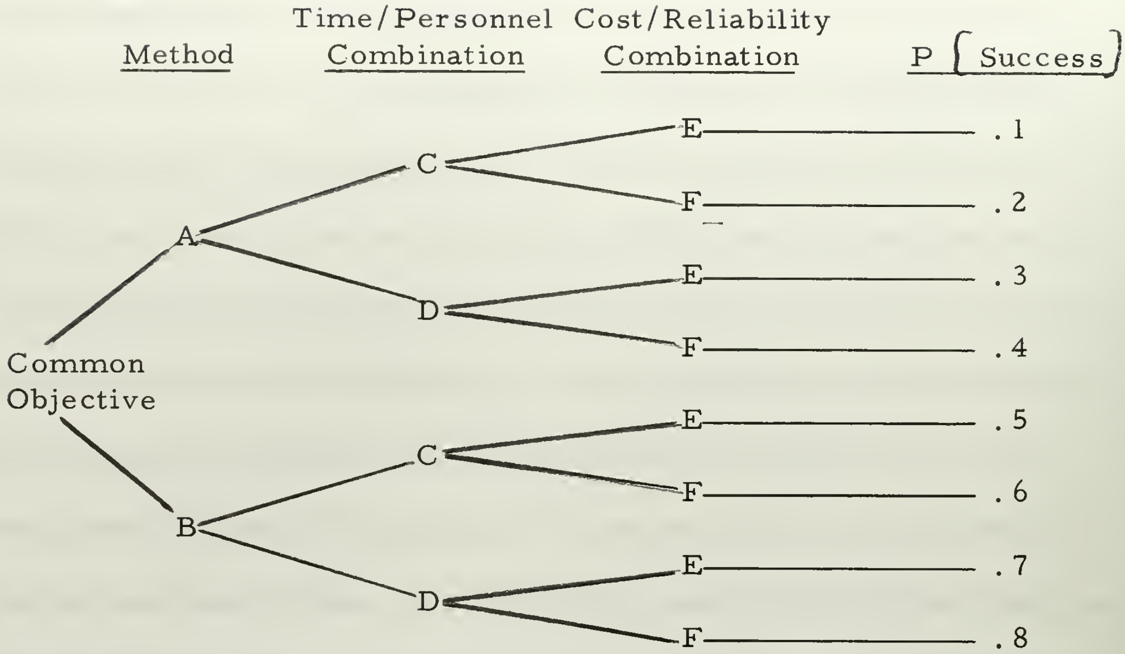


Figure 5-1
Alternative Approaches for a Single Objective

The example probably does not represent any real problem, and the probabilities of success were used to count alternatives, but it is easy to imagine a product which may be achieved by many different combinations of technological approaches, time, personnel, funds, reliability and probability of success. Some of the alternatives could be eliminated on the basis of very low probability of success, but for every one eliminated several new ones could be generated by relaxing the simplifying assumption on dependence of time and personnel, and of cost and reliability. As more refined trade-off analyses are developed, it may be possible to determine optimal and several near-optimal alternative project definitions.

There is a group of hard-to-measure costs that should also be given consideration. (See list below.) They are difficult to include in a quantitative model with any degree of consistency. Rather than omit them altogether, a reasonable approach would be to include (in the TDP or equivalent) the list of these costs, state which of them appear to be significant, and indicate whether or not they have been specifically included in the selection model. The list follows[93] and is most generally applicable to Operational Systems Development projects.

(1) external economies and diseconomies
(2) inherited assets
(3) shared assets (indicate method of pro-rating used)
(4) fixed supply assets
(5) salvage values
(6) spillover costs

If the decision is made to approximate and include the significant costs from this list, they should be included in the R&D cost or total system cost, as appropriate. This must be done consistently--not with just a fraction of the significant costs--and the costs included must be clearly documented.

Program Balance.

There are several aspects of achieving a balanced R&D program. They include the distribution of effort between basic research and development, short-range and long-range projects, offensive and

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[93] B-31, pp 136-147.

defensive capability, and among functional areas. These considerations are again difficult to build into a model. It would be simple mathematically to place upper and lower bounds on each of the categories, but determining proper values for these bounds is another matter altogether. It is quite likely that a satisfactory means of developing the bounds will some day be formulated, but then another question must be answered: over what time period is "balance" required? The random occurrence of breakthroughs makes it unlikely that the upper and lower bounds on projects can be satisfied <u>efficiently</u> at any given instant.

The amount of effort or funds alloted to basic research has received the most attention, and it has been mentioned in previous chapters. It is very closely related to the long-range/short-range distribution of effort. The long-range development programs are based on today's research programs; "applied research and development tend to proceed more rapidly, and at a lower cost, when adequately backed by basic research."[94] There is widespread opinion that more effort should be devoted to long-range basic research projects, but the unsophisticated procedure of stating that X% of the RDT&E funds should be devoted to basic research is apparently the only one available at present. The percent, X is a rather arbitrary number, and will remain that way until some means is developed for accurately measuring the returns on R&D.

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[94] B-42, pp 59.

The concept of balancing the distribution of R&D effort among functional areas such as anti-submarine warfare, anti-war warfare, electronic counter-measures, etc., and between offensive and defensive capability is an interesting one. The R&D funds could be allocated among functional areas in the same manner as the Navy allocates funds among functional areas outside of R&D, but this is not apt to be efficient or effective. Problems and breakthroughs will probably not be evenly distributed by functional areas. Relatively small expenditures may therefore produce high returns in some areas, and very heavy expenditures and large numbers of personnel may be required to obtain any returns in other areas. In economic terms, balance will be achieved when the marginal return per dollar cost, per man-hour, and per unit use of facilities are equal in each area.[95] But even when measurement of R&D returns is refined to the point where this information is obtainable, the marginal returns will be changing frequently, thus requiring rapid feedback on development and great flexibility in programming effort.

The requirement for a rapid reallocation of effort brings up another problem. "Research cannot be turned on and off without producing disruptive effects on the program and the organization."[96] How often and to what extent can the reallocation of effort be made without disrupting program continuity? Some reallocation must be

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[95] A-2, pp 151.

[96] B-42, pp 60.

made to take advantage of major breakthroughs, but excessive stop and go commands waste much time and effort, and lead to discontent among the research personnel.

Within the R&D categories, the allocation of effort is guided by the relative importance of objectives provided by higher levels of management. Further evaluation of this military potential of projects is enhanced by the presence of naval personnel at most research activities, and by the "user-producer" relationship between CNO, and CNR and CND. The proposed increased input of fleet problems and proposals may also be helpful. The potential military worth of a project is a very important criteria for selection and reviewing the program for balance.

The extent to which this information and this approach are used in the research category has been criticized. Stoodley's comments are directed at ONR but they have much broader applicability. He cites the informal nature of communications within ONR as inhibiting the efficient utilization of the Naval Applications Group (Section VI) in recognizing potential applications.[97] He states that the "lack of documentation prevents adequate transmission of information to upper management levels, and results in serious discontinuities in planning during personnel turnover cycles."[98] The increased emphasis on objectives provided from higher levels of management and the phase I

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[97] See reference B-60.

[98] _Ibid._, pp 59.

procedures of bringing the scientists and engineers into the activity's planning function should help to overcome this problem.

A basic issue in balancing a program is whether the military objectives should control the R&D effort, or whether the R&D capabilities and expected returns should govern the military force structure. As usual, neither extreme is apt to provide the best results. The general national defense policy <u>and</u> the technological advances and potential must be combined to formulate an R&D program that is both efficient and balanced. This is the reason that technology is shown as an input in the planning process in Figure 3-1. The initial input is not sufficient, however; as significant new technological potential is perceived, the plans must be reviewed prior to project selection.

<u>A Selection Model</u>.

The measure of effectiveness tentatively suggested previously was the expected military potential of completed R&D projects. The potential value of the military projects has been treated as a military evaluation of the importance of the end product goal of the R&D study. For this measure to indicate the <u>R&D</u> effectiveness, it must be based on the difference between the current capability and that resulting from the project, as well as the "absolute" import of the end product. The subjective evaluation probably is effected by the magnitude of the change, but frequent criticism of the bias toward short range, rapid

return projects indicates that relatively little importance is attached to the magnitude of the increase in capability.

In the section on balance, the concept of efficiency was introduced briefly. Intuitively, some projects can provide more return per dollar expended than others. In more precise terms, the optimal combination of projects is obtained when the marginal product per dollar is the same for all input factors.[99] The measurement problems involved have already been pointed out. Attempts are being made to determine the cost of a "unit of research" and the personnel and use-of-facilities costs for various types of R&D;[100] these may provide useful information in determining efficiency but still require measures of R&D output. Even when the desired measures of effectiveness of the R&D output become available, the concept of efficiency will still be very difficult to apply. The application requires _a priori_ estimates of efficiency, and the results of R&D are designed to upset the equilibrium conditions upon which efficiency allocations are based. This makes the predictions extremely difficult.

The following procedure for obtaining the total program effectiveness from the individual project values is a modification of Shaller's presentation,[101] eliminating project funding level factors and adding some of the considerations discussed in this chapter.

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[99] A-2, pp 151.

[100] B-59, pp 11; A-12

[101] B-54, pp 9-12.

$e_{ij}$ = effectiveness contributed by the $i^{th}$ project to the $j^{th}$ objective

$E_i = \sum_j e_{ij}$ = effectiveness of the $i^{th}$ project

$E_j = \sum_i e_{ij}$ = effectiveness contributed to $j^{th}$ objective

$E = \sum_i E_i$ = total program effectiveness

Let $E_{i_o}$ = effectiveness of current capability addressed by $i^{th}$ project

Then $(E_i - E_{i_o})$ = magnitude of improvement proposed by $i^{th}$ project

The process of evaluating projects in terms of their contribution to the organization's objectives is a good approximation of the subjective evaluation for project selection, and for this reason it is a very useful technique. But it stops short of the desired total measurement because of its assumption of independence. The incremental value of completing combinations of projects should also be included.

If each alternative method of achieving a specific goal is defined as a project, the projects are then either in the program or out. The funding level is included in the definition of the project rather than in the variables $x_i$ which the mathematical model is designed to evaluate.

This gives $x_i = \begin{cases} 1 & \text{if the project is to be included in the activity's R\&D program} \\ 0 & \text{if the project is not included} \end{cases}$

If the incremental value of completing both projects i and k, where k is used to index the same n projects as i, is designated $d_{ik}$, the total program effectiveness is $E = \sum_i E_i x_i + \sum_i \sum_k d_{ik} x_i x_k$ ; where $d_{ii} = 0 \; \forall_i$. These incremental values represent increases in the military capability addressed by each project individually, as contrasted with more general spillover costs or benefits in different areas.

The problem of whether effort should be allocated according to the true value of the project or according to the magnitude of the improvement over existing capabilities has not been resolved. Reasonable arguments may be formulated for either approach; it is reasonable to include both. Let $E_i$ represent the expected potential value of the new product, and let $E_{i_o}$ be the value assigned to the current capability in the $i^{th}$ category. The $E_{i_o}$ can be provided by top management, and this will provide a consistent basis for estimating the $E_i$. The difference $(E_i - E_{i_o})$ is the second consideration. How to incorporate this value depends on the relative magnitudes of the $E_i$ and $E_{i_o}$. If the differences are generally large relative to $E_{i_o}$, then an additive term would be easiest. If the differences are relatively small, a multiplicative expression would give greater weight to the magnitude of the advance. In the latter case, the total program effectiveness becomes

$$E^* = \sum_i (E_i)(E_i - E_{i_o})x_i + \sum_i \sum_k d_{ik} x_i x_k$$

The obvious refinement would be to express the incremental values of pairs of projects as differences over the existing combined capabilities, but this may be too much to expect for the present. When more experience is gained in making the approximate quantification of the subjective evaluations, it could be included. A further extension would assign incremental values to various combinations of three or more projects. The extension is desirable, but not practical due to the difficulty of making the estimates and to the inaccuracy of the estimates in the rest of the program. Again, it may be added as more refined estimating skills are developed.

The obvious constraints are cost, personnel availability, and the availability of facilities. It would be relatively easy to write the constraints on the total R&D expenditures, total personnel, and total facilities, but to do so would overlook several important points. The activity's research personnel do not all possess the same skills and training, and they probably cannot be efficiently assigned to projects without examining their skills. It may be possible to categorize the research personnel at each activity and provide a constraint for each category. Let

$P_\ell$ = number of available personnel in category $\ell$, $\ell = 1, 2, \cdots, L$

$p_{i\ell}$ = number of category personnel required for project i

Then

$$\sum_i p_{i\ell} x_i \leq P_\ell$$

But the personnel assigned to the $i^{th}$ project may not be required for the duration of the project. It is desirable to include time periods in the personnel constraint as follows:

Let $P_{\ell t}$ = number of available personnel category $\ell$ during time increment t

$p_{i\ell t}$ = number of category $\ell$ personnel required for project i in time increment t

Then

$$\sum_i p_{i\ell t} x_i \leq P_{\ell t}, \quad \ell = 1, 2, \cdots, L \; ; \; t = 1, 2, \cdots, N$$

A similar argument may be presented for the available facilities:

Let $F_{mt}$ = available facilities in category m in time intcrement t

$f_{imt}$ = $i^{th}$ project's requirement for facility m in time increment t

Then $\sum_i f_{imt} x_i \leq F_{mt}$, m = 1, 2, ..., M; t = 1, 2, ..., N

For both cases, the possibility of acquiring more personnel or expanded facilities, or of "renting" them (i. e., contracting the project or portion of it, or hiring consultants) must be considered.

The cost constraint is more complicated. The activity will have a budget constraint, but the R&D costs are not the only ones that effect project selection. The total system cost estimate is the Navy's major concern, and to consider only the R&D costs would be an undesirable suboptimization. The R&D cost constraint can be written easily: $\sum_i RC_i x_i \leq R$. The R&D budget R should be reduced by personnel

salaries and operating expenses of facilities. It can be modified to handle successive annual (expected) budgets. The predicted procurement and operational costs will not use up the full Navy budgets for following years, but it is difficult to establish what percentage or what amount would be acceptable.

The current decision process requires a review of the TDP to ascertain whether or not the total system, operating and maintenance, and procurement costs will be acceptable. This cannot be written as a general constraint. Rather than neglect the total cost, however, it may be included in the objective function. Following the same reasoning as used for project and program effectiveness, the modified objective function is

$$\text{Maximize } E^{**} = \left\{ \sum_i \left[ K \cdot E_i \, (E_i - E_{i_o}) - C_i \, (IOC_i - IOC_{i_o}) \right] x_i + \sum_i \sum_k d_{ik} x_i x_k \right\}$$

where $C_i$ = total cost of project i

$IOC_i$ = investment and all operational costs of project i

$IOC_{i_o}$ = replacement and all operational costs of current capability i

K = proportionality constant to adjust relative size of cost and effectiveness values

Some comments on the new quantities are in order. The total cost $C_i$ represents all costs associated with project i, from R&D to operating and maintenance costs. $IOC_i$ and $IOC_{i_o}$ are used rather than total costs in the difference expression to compare the introduction

of the new system with continued use of the old. By making the cost expression the subtrahend, the model will properly handle cost-reduction projects. The difference $\left[IOC_i - IOC_{i_o}\right]$ will then be negative and it is preceded by a minus sign. Hence the objective function maximizes the cost reduction. In this type of project, the $\left[E_i - E_{i_o}\right]$ will go to zero if the same level of effectiveness is maintained. The particular costs used in the objective function may be changed if other costs are considered as giving a better measure of cost differences; e.g., $\left[C_i(C_i - IOC_{i_o})\right]$ could be used. Whatever costs are adopted, they should be used consistently for all projects.

The proportionality constant K is required to convert units of military worth to dollars. It need not be a precise conversion. It should adjust the relative magnitudes of effectiveness and cost to suit the subjective evaluation of that comparison.

One additional consideration that should be built into the model is the length of time required to complete a project, $\Delta T_i$. The time requirements for use of facilities and personnel may not be sufficient for this purpose. Since in general it is desired to minimize the time required for development, the time consideration may be included with the cost expression. The $\Delta T_i$ could be used directly as another factor in the cost expression. This may exaggerate the importance of the time factor, and for cost reduction projects, the model would actually maximize time required to complete projects. Since the total value of each project considered can be assumed to be positive

it may be desirable to multiply that expression by $\left[\ell n(a+\Delta T_i)\right]^{-1}$.

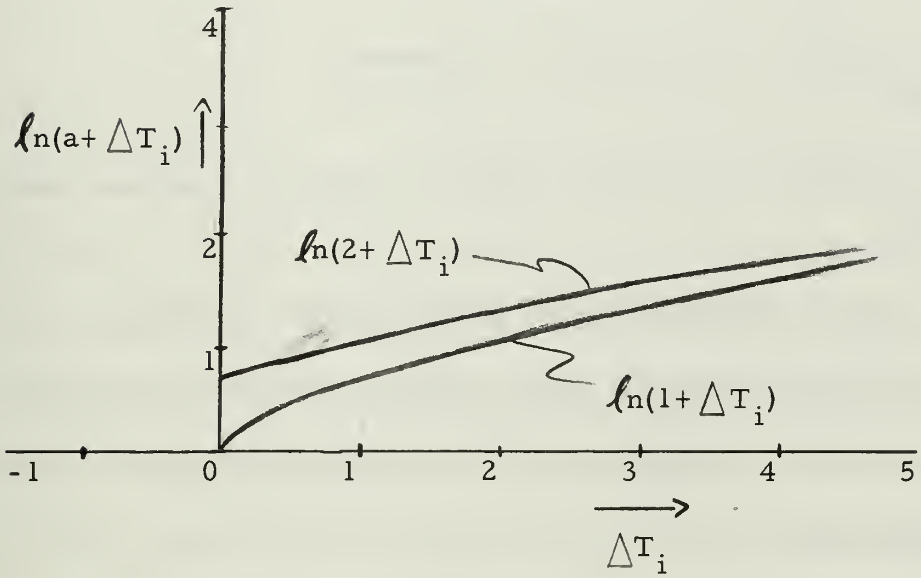
This gives

$$E^{***} = \sum_i \left[\ell n(a+\Delta T_i)\right]^{-1} \left[K\cdot E_i(E_i - E_{i_o}) - C_i(IOC_i - IOC_{i_o})\right] x_i$$

$$+ \sum_i \sum_k d_{ik} x_i x_k$$

The +1 in the expression $\ell n(1+\Delta T_i)$ eliminates negative values. A plot of the expression $\ell n(a+\Delta T_i)$ is shown in Figure 5-2 to display the effect of project length on the objective function. (Note that the reciprocal of this expression is used.) Use of the expression decreases

Figure 5-2
Model Treatment of Project Duration




the effect of errors in project time estimates and the relative importance of time in the overall expression. It may be desirable to remove the steep slope at the origin by increasing the additive constant.

This method of indicating a preference for project duration is subjective and it is not a true discounting procedure. It represents a consideration that should be made, but the precise method may be modified to fit the subjective evaluation of time preference.

Since the alternative methods of achieving a specific goal have been defined as separate projects in the model, program constraint #4 must be included to prevent undertaking more than one alternative path. Let

$Y_y$ = group of alternative paths to single specific objective

$Z_z$ = group of alternative paths which may be considered for parallel development for a single specific objective.

Then

$$\sum_{i \in Y_y} x_i \leq 1 \quad , \quad y = 1, 2, \cdots, Y \text{ groups}$$

$$\sum_{i \in Z_z} x_i \leq s \quad , \quad s = 1, 2, \cdots S; \; z = 1, 2, \cdots, Z \text{ groups, and}$$

s = number of parallel paths which may be considered.

The introduction of parallel paths requires a modification of the objective function. Discussion of this modification will be temporarily postponed.

Constraint #5, $x_v \leq x_w$, for specified pairs of values for v and w, is required if project v may be undertaken only if project w is also included in the program.

The model as presented is deterministic, which is certainly undesirable. The two probability statements obtained in the evaluation process may be incorporated as follows:

Define $\beta_i$ = probability that project i will be successfully completed

$\gamma_i$ = reliability of project i

Then $SC_i$ = total system cost of project i

$E_i = \beta_i V_i$ = expected effectiveness of $i^{th}$ project or expected military value of $i^{th}$ project

$$C_i = RC_i + \frac{1}{\gamma_i}\left[SC_i - RC_i\right]$$

With the probabilities of success defined, the modification of the objective function to handle parallel R&D can now be developed. It will be assumed that the parallel development paths are selected so as to be mutually independent. If two projects are selected, the breakthrough required for each must depend on different technology. If this is not the case, parallel development may be recommended in more instances than desirable. Since one of the characteristics of parallel development paths is technological independence, the assumption of independence is not as damaging here as it is in most cases. These considerations should be made in defining the parallel development project groups.

For s = 2 (parallel development permitted, but not required, on 2 paths), the expected value will be increased if 2 paths are included, but it cannot exceed the potential value of successful completion by either path.

If $Y_y = Y_1 = \left[x_1, x_2\right]$, then $\sum_{i \in Y_1} x_i = x_1 + x_2 \leq 2.$

If $x_1 + x_2 = 2$, then $E_1 = E_2 = \left(\frac{1}{x_1 + x_2}\right) \cdot V_1 \left\{\beta_1 x_1 + \beta_2 x_2 - \beta_1 \beta_2 x_1 x_2\right\}$,

where $V_1 = V_2$. Also, $d^*_{ik} = \left(\frac{1}{x_1 + x_2}\right) \cdot d_{ik} \left\{\beta_1 x_1 + \beta_2 x_2 - \beta_1 \beta_2 x_1 x_2\right\} =$

$d^*_{2k}$, where $d_{1k} = d_{2k}$. Similar expressions may be derived for $s=3,4\cdots$

The model and quantities included are summarized in Figures 5-3 and 5-4.

It may be desirable to add constraints to provide balance of effort among functional areas, as discussed in the preceding section. But the manner in which the model is used may make it easier to evaluate the balance of the model output. The sequential manner in which personnel and facilities become available to perform new projects indicates that the model may be applied to the set of "inactive" projects and constrained by the available increments of funds, facilities, and personnel. If projects in progress are also included in the application, it will be desirable to update the estimates of reliability, cost, and probability of success or otherwise redefine the current projects. This will increase the expected value of projects which are progressing well and improve program continuity. If this is not sufficient to attain the desired continuity, an artificial bias may be added for current projects. This would be a rather delicate operation, since too large a bias may result in pursuit of projects that should be dropped.

Successive iterations of the program may be used to investigate changes in the R&D budget, increased availability of personnel and/or facilities, and sensitivity to any of the input estimates. If the constraints on personnel and/or facilities are binding and more funds are available, then the manager may investigate renting or procuring additional personnel or facilities.

Some optimization techniques solve for the funding level of projects rather than simply determining which projects are to be included. (See Brandenberg and Stedry, ref. B-5.) In the model presented, the funding level is based on the definition of the projects as project alternatives, where the alternatives may be similar projects at different funding levels with differences in probability of success or other characteristics. The funding level is determined by the cost estimates of the alternatives rather than by the model.

The model is entirely dependent on the availability of the estimates of potential military value. These estimates are applied subjectively in the current review process. If the values of current forces or capabilities (the $E_{i_o}$) are supplied, they will provide a valuable yardstick for the estimates of future project value, and add greatly to the overall consistency of the estimates. The model is further limited by the use of expected values, but will accept estimates based on minimum, maximum, or other intermediate values.

Figure 5-3
Selection Model Formulation

$$\text{Maximize } E^{***} = \sum_i \left[\ln(a+ \quad T_i)\right]^{-1} \left[K \cdot E(E_i - E_{i_o}) - C_i(IOC_i - IOC_{i_o})\right] x_i$$

$$+\sum_i \sum_k d_{ik} x_i x_k$$

Subject to:

$$1)\ \sum_i RC_i x_i \leq R$$

$$2)\ \sum_i p_{i\ell t} x_i \leq P_t \qquad \ell = 1, 2, \cdots, L;\ t = 1, 2, \cdots, N$$

$$3)\ \sum_i f_{imt} x_i \leq F_{mt} \qquad m = 1, 2, \cdots, M;\ t = 1, 2, \cdots, N$$

$$4)\ \sum_{i \in Y_y} x_i \leq 1 \qquad y = 1, 2, \cdots, Y$$

$$5)\ x_v \leq x_w \qquad v, w \in \{1, \cdots, n\}$$

$$6)\ x_i, x_k, x_r = 0, 1 \qquad i, k = 1, 2, \cdots, n$$

Modifications to include parallel development on independent paths

$$4p)\ \sum_{i \in Z_z} x_i \leq s \qquad s = 1, 2, \cdots, g$$

For $s = 2$,

$$E_i = V_i \left\{ \sum_{i \in Y_y} \beta_i x_i - \sum_{i \in Y_y} \sum_{k \in Y_y} \beta_i \beta_k x_i x_k \right\}$$

For $s = 3$,

$$E_i = V_i \left\{ \sum_{i \in Y_y} \beta_i x_i - \sum_{i \in Y_y} \sum_{\substack{k \in Y_y \\ i \neq k}} \beta_i \beta_k x_i x_k \right.$$

$$\left. + \sum_{i \in Y_y} \sum_{k \in Y_y} \sum_{\substack{r \in Y_y \\ i \neq k \neq r \neq i}} \beta_i \beta_k \beta_r x_i x_k x_r \right.$$

Similar modification of $\sum_i \sum_k d_{ik} x_i x_k$ is required.

Figure 5-4
Model Quantity Definition

$x_i$ = project i, $i = 1, \cdots, n$ projects

$x_k, x_r$ = projects k, r; k & r independent indices for the n projects

$V_i$ = potential military value of project i

$E_i$ = expected military effectiveness of project i, $= \sum_j e_{ij}$

$E_{i_o}$ = value of current equivalent of project i

$d_{ik}$ = incremental expected value obtained from including projects i and k

$C_i$ = total cost of $i^{th}$ project, adjusted for reliability goal

$RC_i$ = R&D cost of $i^{th}$ project

R = total R&D activity budget

$p_{i\ell t}$ = personnel in category $\ell$ required for project i in time increment t

$P_{\ell t}$ = total personnel available in category $\ell$ in time increment t

$f_{imt}$ = facilities in category m required for project i in time increment t

$F_{mt}$ = total facilities available in category m in time increment t

n = number of projects

N = program time horizon

L = number of personnel categories

M = number of categories of facilities

Figure 5-4 (continued)
Model Quantity Definition

$Y_y$ = groups of alternative projects for same specific goal

$Y$ = number of groups of alternative projects for same specific goal

$s$ = number of parallel development paths permitted

$g$ = number of parallel development projects permitted

$\beta_i$ = probability that project i will be successfully completed

$\gamma_i$ = reliability estimate for project i

$SC_i$ = total system cost for project i

$IOC_i$ = investment, operating, and support costs for project i

$IOC_{i_o}$ = replacement, operating, and support costs for continuing current equivalent of project i

$K$ = proportionality constant to convert military values to dollars

$Z$ = number of specific objectives in which parallel development is considered

$Z_z$ = group of projects for which potential parallel development is is considered

$$E_i = \beta_i V_i; \qquad C_i = RC_i + (1/\gamma_i)\left[SC_i - RC_i\right]$$

$$d_{ii} = 0 \quad \forall i$$

The model attempts to quantify the considerations which go into the existing subjective program formulation. Unfortunately it is rather difficult to solve. A linear programming problem with (0, 1) constraints on the variables has been solved by Balas.[102] His algorithm is based on a combinatorial approach which starts with all n variables at 0 and tests a small part of the $2^n$ combinations to determine an optimal solution or indicate that none exists. It can be used to approximate the solution of a similar quadratic program. It may be possible to modify this approach and combine it with decomposition techniques applied to the other constraints to obtain a solution. There are several other approaches that may be fruitful. By redefining the variables to include combinations of projects, the problem may be written as a linear programming model. Some sort of redefinition of variables will probably be necessary to solve the parallel development model, since as written it is considerably more difficult.

For an immediately applicable solution, the manager can define several "good" feasible programs and compute the objective functions for each. Careful examination of the results may indicate places where improvements may be made on program definitions. Another possibility is the elimination of the quadratic expression from the objective function, making a direct conversion to the modified linear programming form. This procedure is described in greater detail in Chapter 9.

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[102] D-1.

As estimating techniques become more refined, a further modification of the model may be desirable and possible. Constraints 1, 2, and 3 may be combined in a single cost restraint such as:

$$\sum_i \left[ RC_{it}(\text{general}) + RC_{it}(\text{personnel}) + RC_{it}(\text{facilities}) \right] \leq R_t$$

where $RC_{it}(\text{personnel})$ = cost of research personnel required for project i in period t

$RC_{it}(\text{facilities})$ = cost of facilities required for project i in period t

$RC_{it}(\text{general})$ = other R&D costs for project i in period t

$R_t$ = total R&D budget in period t

This form of cost constraint must be used with caution, however, since it may imply a non-existent ease of acquiring additional personnel and facilities.

The sequencing of projects and a more accurate time preference may be introduced in the objective function. This requires accurate estimates of project value in each year, accurate estimates of the operational date of the end product, and accurate estimates of project time horizon and salvage value. All of these are difficult to obtain. The constraints above require "units" of research, personnel, and facilities, and the number of units of each type required for each project. These numbers and unit definitions have caused difficulties in previous models. The revised objective function would be of the form

$$\hat{E} = \sum_i \sum_t \left[ KE_{it}(E_{it} - E_{it_o}) - C_{it}(C_{it} - C_{it_o}) \right] x_i \cdot \left( \frac{1}{1+r} \right)^{t-1}, \quad t = 1, 2, \cdots$$

The discount rate r should probably be kept small to avoid the bias toward quick-return projects. Risk should continue to be accounted for with the probability of success and reliability functions.

Without this modification, the program is more heavily dependent on the evaluation phase "project" definition. As the inputs $p_{i\ell t}$ and $f_{imt}$ are defined, the anticipated possible starting times for the project must be built into the alternatives. Procedures to assist this process are outlined in the next chapter.

## Additional Optimization and Estimating Techniques

The model presented in the preceding section is designed to approximate the current selection process and to include the major selection criteria. Numerous models for project selection have been proposed, some of them differing widely in approach from that presented. This section will briefly review a representative sample of other selection procedures.

The industrial dynamics approach to research and development places heavy emphasis on rates: the flow of effort, information, and payments. The recognition of the sequential decision process is its major advantage. Some very interesting aspects of the project life cycle are investigated and areas offering the greatest potential for improvement are identified. Roberts' program for the project life cycle employs some 200 variable equations, 40 initial conditions and equations, and about 70 constants; many of the relationships are

more subjective and more difficult to quantify than those in the model of the previous section.[103]

In 1959, the Naval Research Advisory Committee suggested a model for the discovery and application of knowledge based on differential equations expressing the rates at which the transitions occur from the unknown, to known-but-not-applied knowledge, to applied fact.[104] Their model was reasonably successful in curve-fitting completed projects, but it suffers from the same difficulties as Lanchester's equations. It is very difficult to determine a priori the quantities which will determine the rates of progress, and until these estimates become dependable, the technique is of little use.

The linear programming formulation presented by Stoessl[105] for basic research project selection depends on the definition of a unit of research, assumes that output will be directly proportional to input for all projects, and that projects are independent. The only constraints are cost/budget constraints. Homogeneity of personnel and facilities are assumed. Shaller's procedure for evaluating the contribution of each project to each objective was employed.

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[103] A-14, pp 5-30.

[104] B-42, volume II, appendix B.

[105] B-59.

[106] B-66.

Other models are entirely subjective. Wilcox[106] modified Asbury's presentation to include projects in the order of their value U, $U = QAC + B$, where Q = quality and novelty of the project; A = appropriateness, or utility and usefulness of the project; C = communications; and B = bias, which includes any other characteristic that the manager may consider significant.

Some models used by industry for project selection may be adapted for military use as "rules of thumb." Two examples are given below.[107]

$$\text{Project value index PVI} = \frac{CTS \times CCS \times AV \times P_1 \times \sqrt{L}}{TPC}$$

$$\text{Index of relative worth, } I = \frac{P_2 \times N}{C}$$

The input values are defined as follows:

| | |
|---|---|
| CTS | = probability of technical success |
| CCS | = probability of commercial success |
| AV | = annual volume of sales; units sold |
| $P_1$ | = profit per unit |
| L | = product life in years |
| TPC | = total project cost |
| $P_2$ | = probability of attainment of commercial goal |
| N | = estimated net return--five years |
| C | = estimated future research cost |

Brandenberg and Stedry present a model which is also primarily industry oriented and maximizes the funds available to the firm at the end of a particular time period.[108] Laboratory efforts provide a

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[106] B-66.

[107] A-7, pp 199-203.

[108] B-5.

dollar return to the firm, and borrowing between branches of the firm is permitted at selected lending and borrowing rates.

Charnes and Stedry have developed a chance-constrainted program for "optimal real-time control of research funding" which appears to have an excellent potential.[109] The demand for research is assumed to be known, except for unpredictable changes resulting from operating emergencies or technological breakthroughs. The program perturbs conditions existing at the time of the breakthrough or emergency and computes the required reallocation of effort. It is designed for short-run modifications. A more detailed description than that presented would be desirable; their proposal definitely warrants further study.

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[109] B-12.

## Chapter 6. Management Display and Program Control

All philosophers find
Some favourite system to their mind.
In every point to make it fit
Will force all nature to submit.

J. L. Peacock
"Headlong Hall"[110]

The philosophy employed in these chapters is to avoid forcing the Navy to submit to a model and instead require the model to fit Navy R&D. As work is completed, facilities and personnel become available for new projects. The manager reviews the reports on a number of alternatives to select the ones to be undertaken. The model accepts the primary characteristics of the alternatives as inputs, combines this information with the facilities, funds, and personnel available, and computes the alternatives to be included in the program based on the approximate expected military worth of the proposals.

Iterations can be performed as additional personnel and facilities become available, and the planned program can be outlined as far in advance as the timing estimates permit. It is desirable to perform advanced iterations even when the manager is concerned only with the immediate selection. It may reveal that a major increase in

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[110] A-9, Chapter 9.

potential results from waiting for more personnel and facilities, indicating that a temporary increase of personnel assigned to phase I and II evaluation is desirable. The model will readily accept changes in projects caused by breakthroughs or unexpected difficulties.

The model requires and produces a great deal of information that is difficult to grasp without a visual presentation. The evaluation system described provides consistently derived information on the alternatives. The manager must keep track of all current projects and the times at which additional facilities and personnel will become available. This chapter suggests a procedure to simplify this task.

## PERT

The TDP procedures require that PERT diagrams, or similar scheduling presentations, be developed for each project. This chapter is concerned with the R&D portion of the PERT diagram. The procurement portion and the problem of putting the end item into operation are developed for use elsewhere in the planning organization. A summary of the availability of facilities and perssonnel can be included with the PERT diagrams. The project PERT diagrams show the interrelationships of various phases of project development, and the expected time required for completion. PERT/TIME techniques employ a modified beta distribution based on the most likely, worst possible, and best possible times to

completion. The interrelationships of development activities and the time estimates are combined to indicate expected project completion time and to identify the "critical path(s)".

The system has been criticized for its optimistic estimates and reliance on expected values. The PERT tendency to underestimate is probably not significant in comparison with the errors in R&D time estimates. The tendency may result from estimating errors rather than the PERT computations even in areas where the uncertainty is less pronounced than in R&D. There are techniques available which modify PERT computations to account for the variance of activity completion (e.g., the Clark Bias Technique), but again, the errors in the R&D estimates make the required increase in computational difficulty unjustifiable. With or without the optimistic PERT errors, the diagram and computations tell the manager which activities require special attention. This is the greatest contribution of the system; it guides the project manager in allocating effort within the project.

It has been observed that PERT is seldom used on small projects (under $10,000). Hardy presents a forceful argument for using PERT on much smaller projects. He computes the cost of employing PERT/TIME as about 0.1% for large projects and between 1.0% and 2.0% for small projects.[111] For projects involving less than 15-20 activities, the initial computations may be made quite easily and quickly

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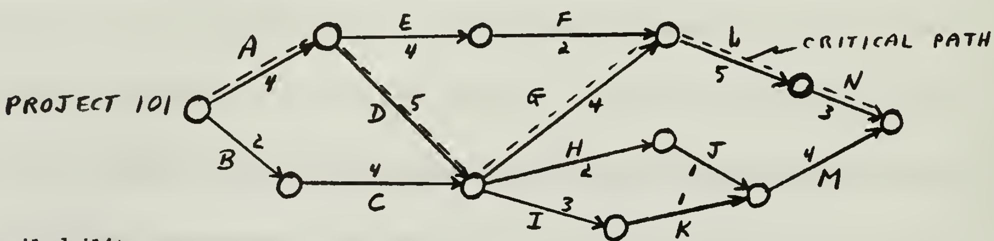
[111] B-27, pp 3, 14.

by hand, eliminating the cost of solving the problem by computer. Progress can be indicated on the initial diagram and this presentation can be used in controlling project activity without additional computer runs. The information contained in the PERT presentation is essential to project decisions, and PERT is a simple and useful way of keeping track of the information.

To increase the value of PERT to the activity manager, the utilization of facilities and personnel may be appended to the project activities, or that information may be presented in summary form omitting the internal reassignment of personnel and use of facilities. A sample display containing this information is shown below.




<u>Availability</u>

| | | | | | | |
|---|---|---|---|---|---|---|
| Personnel | type 1 | -10 | | -5 | +8 | +7 |
| | type 2 | -5 | | -4 | +7 | +2 |
| Facility | type 1 | | -40% | | +40% | |

Figure 6-1
PERT/TIME and Resource Availability

A modification of PERT techniques to permit inclusion of alternative paths to completion, not all of which must be traversed, has been developed by Dr. L. M. Crumley and M. A. Wilson at the Re-entry Systems Department of General Electric. The technique

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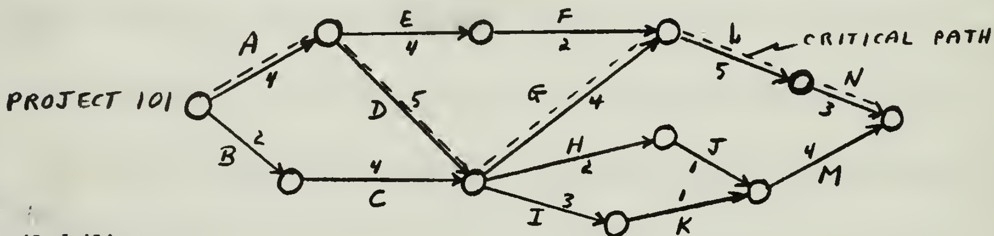


Availability

| | | | | | | |
|---|---|---|---|---|---|---|
| Personnel | type 1 | -10 | | -5 | +8 | +7 |
| | type 2 | -5 | | -4 | +7 | +2 |
| Facility | type 1 | | -40% | | +40% | |

Figure 6-1
PERT/TIME and Resource Availability

A modification of PERT techniques to permit inclusion of alternative paths to completion, not all of which must be traversed, has been developed by Dr. L. M. Crumley and M. A. Wilson at the Re-entry Systems Department of General Electric. The technique

is called ARMNET, for Availability, Reliability, Maintainability Network Evaluation Techniques.[112] It is useful when all the courses of action required for completion cannot be determined with complete certainty. In addition to time distributions, each activity has associated with it a conditional probability of traversal. (In conventional PERT, all traversal probabilities are 1.0.)

ARMNET is a computerized Monte Carlo simulation. The program first checks the consistency of the inputs and then proceeds through the networks. Arcs are selected at random from the traversal probabilities and times are selected at random from the activity time distribution. When a node is occupied via two or more arcs, the longer path is used. When the terminal mode is reached, the total network passage time and path taken are recorded. The process is then repeated a specified number of times to obtain the distribution of project completion times.[113] Attempts are being made to obtain an analytical solution to replace the Monte Carlo technique.

A similar variation of PERT was developed by Eisner specifically for scheduling R&D projects. The transition probabilities are used to determine the entropy of the system and indicate the relative likelihood of proceeding to completion via various paths. This information is then combined with the standard PERT computations.[114]

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[112] B-2.

[113] B-2, pp 8.

[114] D-2.

The PERT diagram not only provides essential management information but also assists the evaluators in phase II in making their cost and time estimates. It can be used to determine manpower requirements by skill and time period.[115] Another modification of PERT has been presented by Freeman to evaluate the effect of changes in end product design specifications. The technique, DESM (Development Evaluation and Specification Modification System), combines network and statistical analysis, and utilizes specification versus time trade offs.[116] The potentials of PERT and other network analysis techniques are great, and further exploration of this area can be expected to provide increasingly effective management aids.

Tree Diagrams

The use of tree diagrams in R&D planning has also been advocated by several authors. Stoodley recommends it for displaying the successive reduction of an operational need into technological support requirements as a means of increasing the sensitivity of the research program to the problems of the operating forces.[117] Hill extends the use of the tree diagram to display progress of projects toward the objectives.[118] These applications are oriented toward basic and

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[115] A-3, pp 124-146.

[116] A-3, Chapter 10.

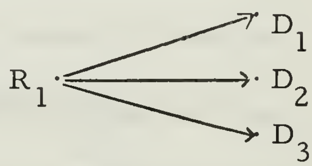
[117] B-60, pp 105-114.

[118] A-18, pp 47.

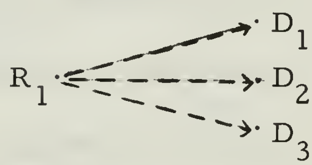
applied research and exploratory development, and the more general definition of objectives in these areas may make the tree diagram preferable to PERT. The PERT diagrams contain additional valuable information, however, and if this information is available in these categories, contributions to objectives may be computed by the model ($E_j = \sum_i e_{ij}$) and displayed with the PERT presentation.

Some graphical techniques for displaying interdependencies are provided by Brandenburg and Stedry.[119] Their dichotomy of "research" ($R_i$) and "development" ($D_j$) projects is retained in the summary below, but the interpretation can be applied to any events or categories.

$R_1$ required for $D_1$, $D_2$, and $D_3$:

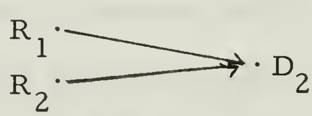



$D_1$, $D_2$, and $D_3$ are facilitated by $R_1$:

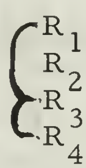



Either $R_1$ or $R_2$ will facilitate $D_1$:


Both $R_1$ and $R_2$ are required for $D_1$:




Mutually exclusive activities $R_1$, $R_3$, and $R_4$:

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[119] B-5, pp. 7.

These techniques may be combined with the tree diagrams to provide additional information on the project relationships.

Multi-PERT

The individual project PERT diagrams may be combined by the activity manager to obtain a display of his entire program, and the combined project utilization of facilities and personnel provide directly the constraints on facilities and personnel. The dependence of projects can be displayed, including parallel development efforts. A simple example of the combined presentation is presented in Figure 6-2. The information on the contribution to objectives has been added to this figure.

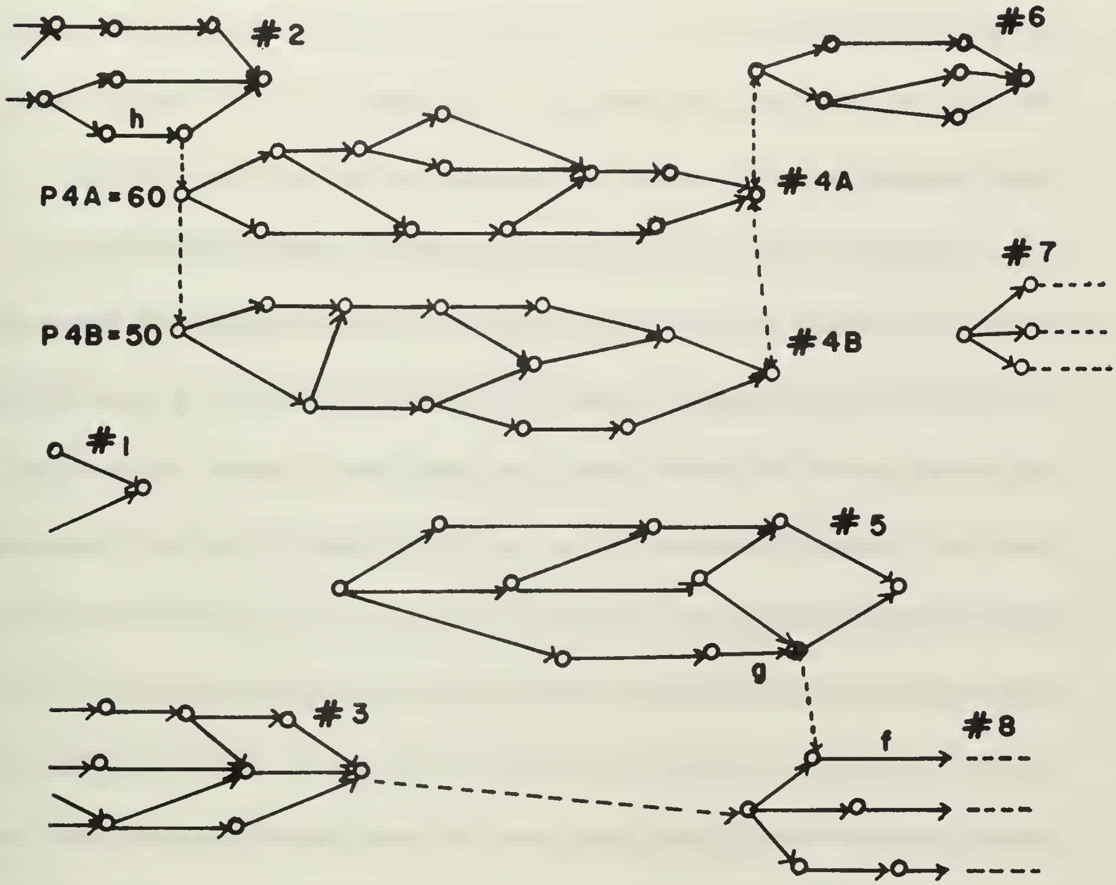
As the projects are completed, the personnel assigned are shifted to phase I evaluation, and personnel already in phase I and II are assigned to new projects. Facilities become available and are scheduled for use by new projects. The "plus" figures in the personnel availability list indicate decision points. Using the availability input figures, the model selects the projects to be included in the program and the selected projects are then added to the display. The availability of funds can be included in the summary information. The plot could be made on absolute time units to improve the visual presentation, but frequent revisions of the estimates can be anticipated. This would require modifications of the entire drawing. It is more practical to approximate the time scale for the initial drawing and include activity times on each arc to permit updating without changing the diagram.

## FIGURE 6-2

### SAMPLE MULTI-PERT DISPLAY

**EXPECTED VALUE**

| | | | | | | |
|---|---|---|---|---|---|---|
| PROJECTS: | 1:100 | 2:200 | 3:150 | 4:650 | 5:250 | 6:150 |
| OBJECTIVES: | A:70<br>B:30 | C:200 | A:75<br>C:75 | A:250<br>C:400 | B:100<br>C:150 | A:60<br>C:90 |




**AVAILABILITY**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Personnel Cat. | 1: +30-37 | -2 | | +20 | -18 | +5 | -7---- |
| | 2: +35-30 | -3 | | +15 | -10 | +6 | -8---- |
| Phase I | :12 10 | 5 | | | 12 | | 8 |
| Facility Cat. I | :(+70%) | (-40%) | | (-20%) | (+40%-10%) | | -25%-- |
| Budget expended | 20% | | | 35% | | 60% | 75%--- |

The project interrelationships in Figure 6-2 are as follows. Project #4 depends on successful completion of activity h of project #2. Project #4 consists of two alternative approaches to improve the chances of attaining its high military value. Successful completion along either path will permit project #6 to commence. Projects #5 and #7 are independent of the information sought by previous projects and await only the availability of personnel and facilities. Project #8 requires successful completion of #3 in order to start, and activity f of #8 depends on completion of activity g of #5.

"Modern Miser" is a similar planning and scheduling tool developed at the Navy's David Taylor Model Basin which warrants study for possible application to the R&D program. It was designed to model naval shipyard operations and uses a basic critical path method. Other features are a cost optimization routine, a procedure for allocating slack time among activities, a man-power leveling process, and a method for scheduling resource allocation.[120] Its major drawback is its deterministic nature, but it is possible--for added programming time and cost--to run multiple iterations using ranges of input variables to gain more information on the set of feasible programs. Revisions to the program to accept the R&D uncertainties would be preferable.

The selection model and the multi-PERT display are mutually supporting techniques. The display is updated to keep management

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[120] B-10.

aware of development problems. This provides the model input for revised definitions of current projects. As projects near completion the estimates of availability of personnel and facilities can be made accurately. This provides the model input constraints on funds, personnel and facilities. The model inputs on proposed projects and their interrelationships are available from the TDP. (A modification of the TDP to make the model inputs more easily obtainable is presented in the next chapter.)

Once these model inputs have been obtained, the computations are made and the revised program is read out. The printout of model computations can include total program effectiveness, the individual project contributions, and the total contributions to functional objectives (the $E_j$) such as ASW, AAW, close air support, etc. This information can be reviewed for program balance. The review may indicate the need to shift effort, and another model iteration can be made, deleting some of the less important selected projects from the admissable set.

When satisfactory balance is obtained--and few changes for balance are anticipated--the model output of selected projects can then be added to the multi-PERT display. The process may be repeated as breakthroughs are achieved or as unexpected problems are encountered. The modified TDP states project interrelationships, anticipated project problems, and project dependence on breakthroughs. This information may be used to update the probability

of success in projects effected by the breakthroughs and problems. The frequency of these events in the R&D process requires many program revisions, and much time can be saved by introducing a numerical and computerized computation of program and project effectiveness.

The model can be used for annual program formulation and longer-range planning, as well as for interim adjustments. It can be used to investigate the effect of budget changes and to compute program changes required by SECDEF and Congress. These revisions must be made rapidly, again emphasizing the advantages of having a mathematical program selection technique available.

Since the model has been designed for use at the activity level, it cannot be used to directly compute the Navy-wide program reallocation. But by running the program for a sequence of increasing budget reductions, the loss of effectiveness can be determined at each activity. This information should be useful in determining where to make budget cuts. The problem of redefining some projects should also be considered. The new alternate solutions and the old ones which were not selected in previous iterations provide for new program formulation. These computations can be made in advance of Congressional and DoD review. It may be desirable to forward this information with the proposed budget requests to give Congress and DoD an indication of the effect of anticipated cuts. The consistency of this procedure depends on promulgation of objectives by the top

levels of management and subsequent discussion of these values within the Navy. There is a continuing requirement for review of these $E_i$ and $E_{i_o}$ values, and this review is going on today in subjective terms to appraise the effectiveness of Navy efforts in a changing environment. The attempt to quantify the subjective evaluation is necessary to relieve top management of the responsibility for studying every detail of the R&D program.

It may be helpful to review the top management control of the R&D process in this context. Briefly, CNO outlines capabilities and goals. The R&D community responds with PTA's or similar documents, which are reviewed by CNO. If the PTA looks promising, a more specific requirement is established and a TDP is written. The review process is repeated. Approved projects are reviewed twice annually thereafter, or more often for major projects in difficulty. The procedures place very heavy demands on top management, particularly in the early stages.

It may be possible to substantially decrease these demands without reducing effectiveness. It has already been argued at some length that current procedures attempt to acquire too much information before it can be evaluated with the accuracy desired for decision-making. Armed with detailed values of current and proposed capabilities, the activity managers can make the preliminary decisions efficiently and effectively. Based on the TDP results, the manager can propose an R&D program for his activity and forward

the program for approval, accompanied by the TDP's. This would reduce the time and extent of the review, permit a comparison of projects which can increase the consistency of the review, and provide the review at a time when a reasonable basis for decision has been established.

Management should not be left in the dark between program reviews, however. The reporting procedures should be used during project formulation to keep management informed. The types of reports desired for control or for general information are quite similar. The use of the modified TDP form suggested in Chapter 7 would satisfy both needs and hence permit "management by exception" in the earlier stages as well. Returning the reports to the originating activity with comments on military value of the proposed or active projects could increase feedback and the accuracy and consistency of the value estimates. Suggestions for modification of alternate project definitions could also be included in the management reaction to the project reports.

# Chapter 7. Flexibility of Control

> The source of most of the more fashionable management techniques is the aerospace industry of the United States. A list... contains some fifty techniques from ABLE (Activity Balance Line Evaluation) to WHISIT (Where in the Hell IS IT? ). It was only a lack of published information on the latter which prevented its immediate adoption.
>
> D. D. Hardy
> Royal Aircraft Establishment
> Great Britain[121]

Hardy's comment serves to put the discussion of the last two chapters in perspective. The selection model and the multi-PERT program summary were not included because they are fashionable things to talk about, and the thesis was not written merely as a vehicle to convey them. They were included because they are useful techniques for R&D management. The model is a reasonable approximation of subjective project selection procedures and may be used for long-range planning and for immediate reallocation of resources required by breakthroughs or emergencies. The multi-PERT concept makes use of information that is already required for the TDP, and provides valuable information for the activity manager--whether he uses the selection model or not. Both the model and multi-PERT recognize and emphasize the dynamic nature of R&D planning, and both assist the manager in controlling his program.

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[121] B-27, pp 3.

The control functions require that data on projects in progress be periodically updated; this is currently done with the TDP's. Criteria estimates become more accurate as work progresses. The revised estimates must be recorded and projects re-defined as work progresses. The necessary information is readily available and no additional reports are required, although some modification and simplification of current reports may be helpful. The model may be used to compute program revisions resulting from changes in military value, cost estimates, reliability, probability of success, and project duration. The model could be programmed to compute the merit of projects omitted from the recommended R&D program to indicate to the manager the advisability of contracting some projects or acquiring additional personnel or facilities. Much of the control of the activity's program can be handled in the framework of the model and multi-PERT, but there are other considerations which are discussed in this chapter.

Modern research administration has become a very complicated and time-consuming process. The danger in control is that it can easily develop into over-planning, which can so wrap the process in red tape that the activity spends all its time planning and controlling and none doing. The observation has been made of some civilian institutions that an increasing amount of research is being conducted on a part-time, transition basis, while the researchers

climb the status pyramid of science administration.[122] This criticism is not as widely applicable as others, and it can be controlled by recognizing the problem, clearly assigning administrative responsibility, and encouraging teamwork.

A major administrative requirement is standardization. Cost analyses must use well-defined and uniform costs in order for the program inputs to be consistent. There must be standardized measurement of project values, and this can be provided by top management in the form of $E_{i_o}$ values. The reporting procedures should be standardized to provide ease of evaluation and review of projects from different activities. Introducing complex procedures to provide the standardization can cause more problems than benefits, and the procedures could be kept as simple as possible.[123]

Administrative decisions can be reached more quickly be reducing the number of coordinating and reviewing units, as well as by standardizing and simplifying the reporting procedures. The bilinear structure of the Navy organization tended to increase the frequency of review,[124] but the May 1966 reorganization moved the Navy closer to a unilinear structure. It has been suggested here that the amount of review from above of the R&D projects in the formulative stages be reduced. The reduction would expedite the R&D program, and

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[122] A-12, pp 47.

[123] A-11, pp 460-472.

[124] B-62, pp 61-72.

keep decisions at levels having more familiarity with the problems, thus providing top management with more time to make major decisions.

Another reason for reducing the amount of top-level review is that the information desired for the top-level decision does not become available until later in the process. The further away from the work level that decisions are made, the more difficult it is to communicate a feeling for subjective aspects such as the probability of success. The attempt to provide information that is not available and the attempt to provide a full understanding of subjective evaluations both increase the time required to prepare what may be a misleading report. The report will also be longer than necessary and thereby increase the time required for review. The sequence of changes in project value, costs, difficulties, and timing estimates requires additional communications and causes an "understanding lag," again increasing the desirability of making the decisions at the working level. Similar criticism has been directed at the Navy's retention of the right to evaluate the wisdom of expenditures and the efficiency of effort in contracted projects.[125] In this case the Navy must keep that right to protect its own interests, but a reduction of the organization level at which the decisions are made may be possible.

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[125] A-14, pp 15-19; B-66, pp 5-6.

In a study of control procedures used in industrial and institutional research and development, Hill found considerable variety in type and quality. The better control programs contained the following features:[126]

(1) total funding authorization
(2) total planned vs. actual man-hours and labor costs, by type
(3) total planned vs. expended materials, by type
(4) indicated overrun
(5) forecast vs. actual completion dates
(6) explanations for deviations from predictions

The techniques used to make the predictions should be included in this list.

Activity management should use the information provided to detect potential applications of value analysis and value engineering that may have been overlooked. The activity managers should be permitted to approve or disapprove most of the Value Engineering Change Proposals (VECP) and incorporate thier own changes, reporting the action taken rather than submitting the proposals for sequential review. In the Office of the Assistant Secretary of Defense (Installations and Logistics) the average time required for processing VECP's was "reduced" (!) to less than forty-five (45) days. The reduction was looked upon quite proudly, although effort was still being devoted to expediting the processing.[127] Forty-five days seems to be a very

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[126] B-28, pp 36.

[127] B-22, pp 34.

long time, and the Navy should be able to do better even in the major changes for which review at top levels is required.

Special attention to transitions between projects can also speed the R&D process. The combined use of the model and the multi-PERT display facilitate planning for the transition. In the late stages of project development, accurate estimates on completion time and the availability of facilities and personnel can be made. The personnel and facilities employed usually decrease in stages as completion is approached, and new teams can be successively built up to undertake the next project. If the practice of assigning some personnel to the phase I and II planning and literature review is followed, the transition is facilitated and the new teams can be ready to use the facilities as soon as they become available. By maintaining a consistently high level of activity, much can be done to eliminate slack periods.[128]

The resource management system and project PRIME encourage managers to use accounting and budgeting procedures as controls rather than regard them as necessary bookkeeping evils. The Comptroller's Office can provide valuable assistance in making and updating cost estimates, and can give the manager the full measurable cost of his operations. Two of the goals of project PRIME are to eliminate the "budget ceiling effect" and the once-a-year approach to funding problems. The "budget ceiling effect" encouraged heavy

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[128] B-64, pp 1.

use of new starts. Full funding requirements for the new starts would not become apparent until later years when funding requirements exceeded the planned budgets. It also created a separation of budgeting and military planning. The annual budget cycle tends to be an annual rush, depriving managers of the time needed for adequate review. This emphasizes the need to combine budgeting and military planning on a year-round basis. It is interesting to note that the programming techniques which modified the budget review have not been without problems--in a revision of the numbered programs, the Military Assistance Program had to be omitted from the computer evaluation for lack of a tenth digit for what had become the tenth program.[129]

A financial and estimating problem that occurs in contracting work is the tendency of competitive bidding to produce highly optimistic cost estimates. This problem is receiving considerable attention, and the type of contracts awarded has been shifting from "cost plus fixed fee" to "fixed fee with incentives." It would be very helpful to attach some of the incentive to improvements in estimating techniques. This could improve estimates and increase the believability of contract bids.

The characteristic problems and breakthroughs of the R&D process require a large measure of flexibility. This is one of the

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[129] B-17, pp 19, 32-33, 68.

reasons why previous chapters have stressed the need for clearly identifying anticipated problems and dependence on breakthroughs in project reports. In monitoring current projects the manager can give added attention to these critical points and be prepared to make adjustments. One means of adjustment which is available in exceptional conditions is the Secretary of Defense Emergency Fund. This fund contains $125,000,000 to $150,000,000 for RDT&E projects. This constitutes a realistic recognition of the uncertainties of R&D, and while no transfer may exceed 7% of the total, the $10,000,000 should provide a good start for most projects.[130] Other indications for program re-evaluation are the loss or acquisition of key research personnel, new information in the field of interest, changes in goals, and the availability of new facilities.[131]

Personnel management is as important in R&D activities as in any other field, and the flexibility requirements of the program give it added emphasis. It has been estimated that a 30% annual turnover of personnel results in job-changing and retraining losses which reduce the activity's effectiveness by 20%. Unfortunately the manager must have considerable flexibility in making personnel assignments to cope with scheduling problems and the differences in R&D project size. This requirement conflicts with the desire of many research personnel to avoid transfers and the breaking-up of teams

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[130] B-8, pp 320.

[131] A-7, pp 197.

that have become experienced in working together.[132] The researchers must learn to accept frequent re-assignment and journeys to other activities and the operating forces to exchange information. The activity managers require this type of flexibility to operate their program efficiently. The increased use of scientists and engineers in planning and evaluation may improve their understanding of these management problems, and the similar increased mobility requirements in industry should also decrease personnel turnover.

The control of R&D effort is basically a communications problem. The dynamic nature of R&D makes it impossible to apply the control at single points in time and at a single point in the organization. The uncertainty inherent in R&D produces a sequence of revised estimates for each project, and rapid communication of the revisions to the activity manager is absolutely essential to efficient control. The classification process permits early identification of interdependencies and formulation of lines of communication for specific projects. The evaluation process reveals requirements for support from other activities to advance the state of the art, and in some cases the entire project may be reassigned. The results of completed--or cancelled--projects must be promulgated to the subsequent development activities to permit application of the knowledge, and

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[132] A-14, pp 132-135.

promulgated to the chain of command and operating forces to obtain additional insight into the military applications.

The information may be exchanged on an informal basis, but it should be followed up by formal documentation. The same types of information are required for classification, evaluation, control, and informative review. Differences occur only in the amount of information available and desired. It therefore appears most reasonable and desirable to use similar or identical forms in all phases. The TDP summary report represents the first step in this direction. Additional information can be filled in at each step in the project's development; the form can be designed to accept successive revisions of estimates without deleting the initial estimates; top management can quickly determine which portions are of interest--and if additional information is desired, most of it will be right there. The information included on the report will differ in type and amount with the program category. Figure 7-1 suggests a possible format for the report and lists the information to be included. Some of the categories permit entries from the top-level review and thereby increase system feedback.

The responses of top management officials in industry to an opinion survey on reports to management indicated that the following improvements were desired:[133]

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[133] A-7, pp 339. Citing the "Chemical and Engineering New," January 20, 1958.

40% better conclusions
32% more stress on long-term implications
32% more stress on dollar implications of findings
22% shorter reports
21% more graphic material
13% less scientific
11% more stress on new product implications

The form suggested in Figure 7-1 scores well on these points, and the 22% who want shorter reports should be ecstatic. The survey is ten years old, but judging from the current literature on R&D, it is still applicable. The increased work load in R&D has probably increased most of the percentages more rapidly than improvements could be made.

One reason for the wordiness and great volume of reports may be the mistaken feeling that unless all thoughts which occurred in project evaluation are reproduced in the report, the expense of the study cannot be justified. The final reports often appear to be project work books, rewritten in the best prose. This is not only unnecessary in reports, but undesirable as well. The work book can be kept (but not rewritten) and should be of continuing use throughout project development.

The value of a centralized oontrol point, or more accurately--centralized coordinating point--was suggested in discussing the classification process. Control and review for program balance would also be well served by a centralized coordinating office. R&D category review is currently performed by CNR, CND, and DCNO(D) and CNO, ASN(R&D), and SECNAV perform subsequent review.

Figure 7-1
Multi-purpose R&D Project Reporting Form

| Page | Contents |
|---|---|
| 1. | Administrative information. Project title, category; date and location of entry into system and source of proposal. Activity and key personnel assigned; phone number. Brief statement of problem. |
| 2. | Problem definition. Full description of problem. Objectives; potential military applications and value. Characteristics of end item. Value of current capability. Prior related studies consulted. Revisions, dates, and reasons. |
| 3. | Outline of alternative technological approaches. Revisions, dates, and reasons. |
| 4. | PERT diagram with time estimates, and R&D requirements for personnel and facilities. Revisions, dates, and reasons. |
| 4A, B, . . . | Repeat for alternative approaches ("project definitions.") |
| 5. | Cost summary: total system and subsystem. R&D, procurement, operating, maintenance, and support costs. Costs for current capability. Revisions, dates, and reasons. |
| 5A, B, . . . | Cost estimation worksheet, indicating basis for estimates and more detailed cost breakdown if required. Revisions, dates, and reasons. |
| 6. | List hard-to-measure costs shown on pp . Indicate which are significant, why, and whether estimates have been included. Revisions, dates, and reasons. |

Figure 7-1 (continued)
Multi-purpose R&D Project Reporting Form

| Page | Contents |
|---|---|
| 7. | Reliability goals for system and subsystems. Revisions, dates, and reasons. |
| 7A, B,... | Reliability test requirements, methods, and results. |
| 8. | Description of specific problem areas, reliance on break-throughs. Probability of success. Revisions, dates, and reasons. |
| 9. | Project interrelationships. Incremental values of pairs of projects. Revisions, dates, and reasons. |
| 10. | List of all assumptions. Discussion of effect on project. Revisions, dates, and reasons. |
| 11. | Trade offs in terms of alternative project definitions: cost-time-reliability-probability of success-personnel required-facilities required-potential value. Revisions, dates,and reasons. |
| 12. | Remarks on any unusual circumstances pertinent to project selection or development. Dates. |
| 13. | Recommendations; conclusions; objectives achieved. Dissenting opinions. Revisions, dates, and reasons. |

A small group of personnel could provide bookkeeping services for this review by combining the activity multi-PERT presentations and the report forms suggested in the previous paragraph. This would reduce the review to evaluation and decision-making; the bookkeeping should not be included in the review by top levels of management. The same office could be used for both the initial classification and final arrangement of projects for review. The combined report is designed to facilitate review by top-level management, but it can be almost as valuable to each R&D activity by providing a convenient and informative summary of what is going on in other activities.

## Chapter 8. Program Feedback and Evaluation

> Today is the outcome of yesterday's research and invention; and one can perceive the future unrolling in the technology of the present.
>
> Dr. William A. Hamor
> Senior Director of Research
> Mellon Institute[134]

The lack of a well-developed data bank to support project planning has been mentioned frequently in this presentation. Some of the techniques proposed will require new measurements and new data. There is much valuable information in the history of projects that could be used to evaluate and improve management planning--valuable information that is currently receiving a frightening lack of attention. These subjects are discussed in this chapter.

### Data Bank

A great deal of data is needed to estimate various costs, time requirements, reliability and other project characteristics. Much data has already been collected and many estimating relationships have been derived. The NARDIS data system discussed in Chapter 1, the CNA CIRCUS (Cost Information Retrieval and Characteristics Utilization System),[135] and the computerized data evaluation system

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[134] A-7, pp 1.

[135] B-45, pp 1-2.

associated with the Pacific Missile Range are examples of activities devoted to correcting the data deficiencies.

A major problem being attacked by these activities and others is the inconsistency and lack of explanation of data. The quantification of test results and observations reduces the information available in the sense that unusual results and their causes become obscured in statistical averages. Working with raw data can often uncover such details, and the Operations Evaluation Group of CNA is currently using this approach (albeit not completely by choice). But some of the data now available suffers from a much more serious lack of explanation. It is often impossible to determine what quantities were measured. Poorly defined and completely undefined quantities abound.[136] Some statistical analyses are required to combine such measurements from different sources, thus deriving estimating relationships for who-knows-what. And these peculiar combinations may be all the planner has available for making his estimates.

Another major difficulty is that the concrete and measurable variables are often unrelated to the effort required to get the job done.[137] This problem is most apparent in attempts to measure the progress or output of R&D activities. The number of published papers, the number of patents, the number of advanced degrees held by activity personnel; all have been used to evaluate the

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[136] B-34, pp VII-9.

[137] A-14, pp 167.

effectiveness of R&D activities. These elements are of some interest, but the emphasis placed on them has distorted whatever measurement value the quantities may have had.

The difficulty of identifying and measuring the critical variables has caused them to be omitted from planning altogether in some instances, omitted from computational models in most cases, and omitted from post-operational evaluation almost universally. When they are omitted from the final evaluation of an operable product or system (when they theoretically could be measured rather than predicted), <u>no</u> information is acquired on which to base future estimates. With no new information, the omissions will continue.

There are many instances when decisions have been based on informal communications.[138] The undocumented decisions provide no basis for review at higher levels, and no basis for subsequent analysis of the decision if the project goes awry or achieves unusual success. Planning discontinuities arise during personnel turnover in activities where this informal decision-making is practiced.

It is also necessary to develop estimating techniques which may be applied early in project formulation. The critical variables and estimating relationships will not be sufficient if they cannot be accurately identified until midway through project development. It was suggested earlier that the entire sequence of estimates be preserved and compared with the final measured costs. From this information it may be possible to develop a sequence of empirical

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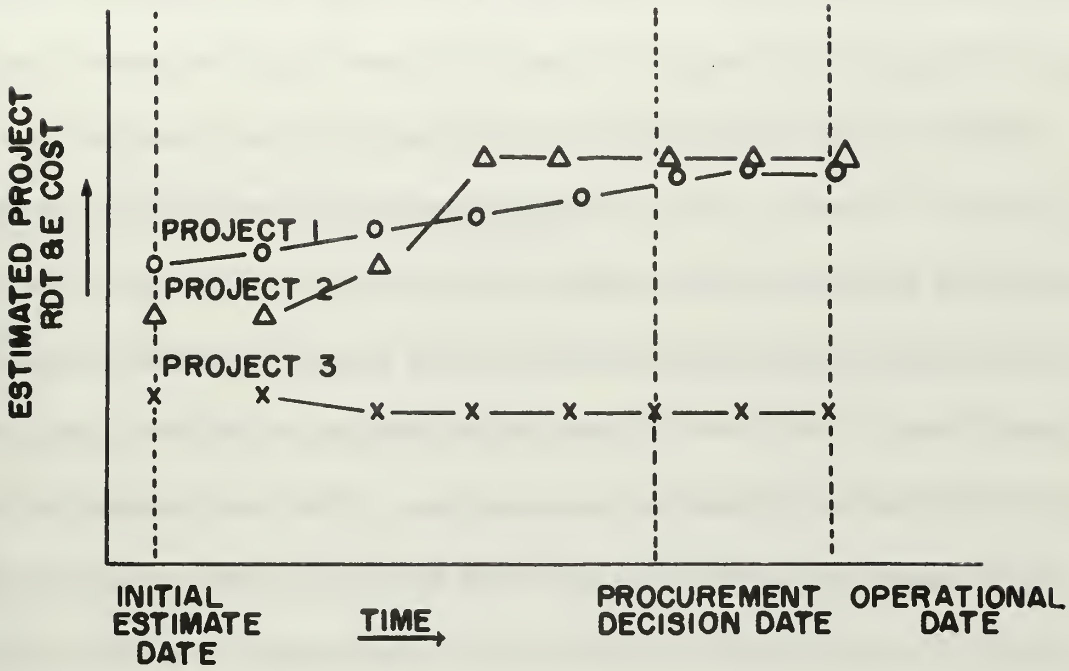
[138] B-60, pp 58-59.

estimating techniques which compensate for the large initial errors. There are indications that the errors follow a general pattern. Some studies have used error-averaging techniques based on symmetrical distribution of estimates about the final project characteristics, but the repeated underestimation of both cost and time requirements does not warrant this assumption of symmetry.

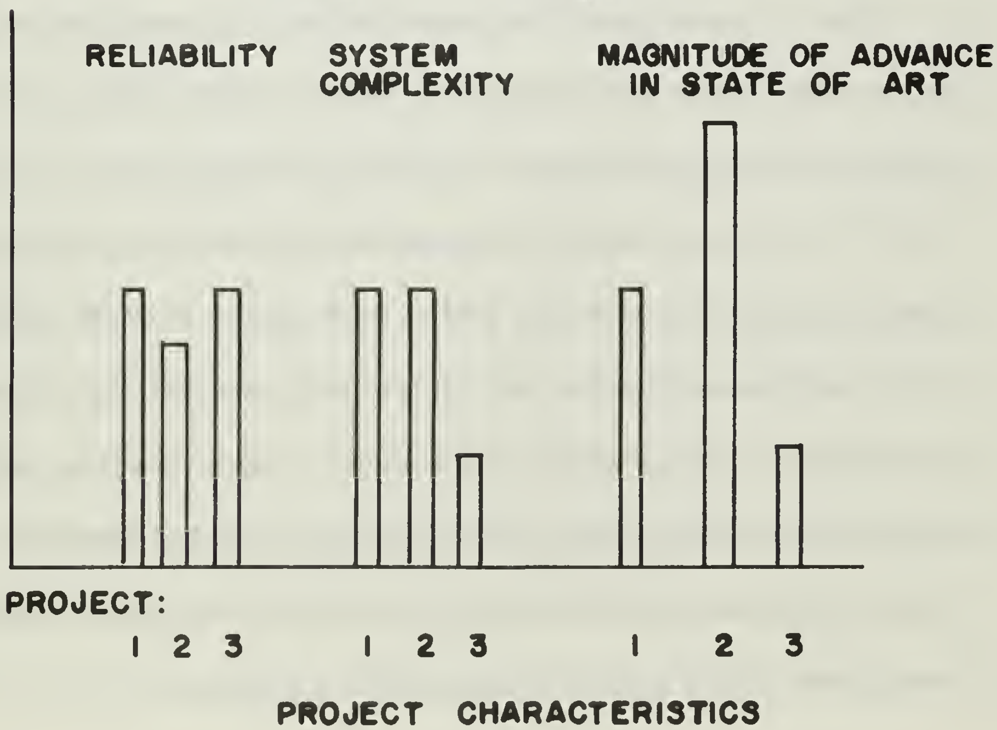
A severe limitation of statistical analysis is that no matter how accurate the data, and no matter how large the sample size, the results are valid only over the observed range of variables. The need for extrapolation is a fundamental characteristic of the R&D process. This makes estimating much more difficult and uncertain. The engineering evaluation of the project may provide enough insight into differences between the project under consideration and the statistical average of previous projects to permit more accurate estimates. To do this consistently, it is necessary to document and explain the statistical presentation. A record of individual projects of a particular type, studied within a single activity, may be more useful than the statistical combination of the projects. An example of this type of estimating relationship is shown in Figure 8-1. Estimates of other project characteristics could be plotted. Graphs such as these, combined with the multi-purpose reports suggested in Chapter 7, can help the manager convert engineering evaluations into percentage points of the distribution of similar projects characteristics or permit extrapolation beyond previously observed values.

FIGURE 8-1

PROJECT ESTIMATES AS A FUNCTION OF TIME TO COMPLETION




ACCURACY OF ESTIMATES



Since there is a great deal of data required in a great number of locations, it is reasonable to ask whether a centralized automated data processing office is necessary. Centralization has been suggested in the classification process and in collecting and sorting scheduled and current projects from the various R&D categories for overall review. NARDIS partially satisfies this requirement for data processing. In this case, however, there are some excellent reasons for maintaining the data at the activities, rather than in a central location. The activities which collect the data will generally have the greatest continuing need for it. They have the best understanding of the data, and use it to develop various estimating relationships. They can up-date the data more conveniently and quickly if they retain it in their own files or their own ADP system. There is also less danger of stripping the data of its engineering information.

What is required is the promulgation of a consolidated list of the types of data which are available. Several studies have been conducted using very rough estimates of project characteristics on which a great deal of recent, accurate, and useful data have been collected. The responsibility for collecting and combining the activity data availability lists could be assigned to the centralized coordinating office mentioned previously. The combined list should be made available to all R&D activities and all offices which undertake planning studies. The Comptroller's Office should review the activities' cost data, a service prescribed in the Resource Management System.

The centralization of the data processing activity shifts the burden of collection and communication and provides an integrated data system. It should be made sensitive to the activity needs for estimating relationships, and it may improve the estimating relationships by providing them with a broader base. It also presents an opportunity to examine differences in performance among activities working on similar items.

New Data from Proposed Techniques.

Perhaps the most interesting addition to the data bank is the information on military values of projects and operational equipment. The best place to start estimating these values is with operational systems or components, on the assumption that it is easier to evaluate existing equipment than to predict values of products in development. The values of the existing capabilities serve as a yardstick for evaluating proposed changes; a further measuring aid may be obtained by comparing cost reduction projects with increased effectiveness projects. This would place the military worth on an approximate dollar basis and establish a means of estimating the value of K. These values are also needed for planning allowance lists for shipboard spare parts.

The acquisition of this data in any form will provide an improved measure of the return on R&D, a quantity which is sorely needed. The suggested measure is the first portion of the objective function of the model: $KE_i (E_i - E_{i_o}) - C_i (IOC_i - IOC_{i_o})$, unit time. If the quadratic form of the objective function can be refined to obtain $d_{ik}(d_{ik} - d_{ik_o})$, this should also be included. An analysis of this measure by categories

may provide quantitative information on the best allocation of effort among the R&D categories, but the values must be assigned consistently to achieve this. Unfortunately these measures are most difficult to make on basic research projects, where the need for allocation guidance is greatest.

The values obtained over a period of time may also be used to establish a cut-off value for inclusion of a project in the program. The cut-off, or series of cut-off levels dependent on the existing workload and the number of alternatives available for consideration, could be used to reduce the computations required in the model. The repeated use of these quantified subjective effectiveness measures should also lead to improved estimates.

The data on facilities, personnel, funds, and time may be used to improve estimates of these quantities, and ultimate to an evaluation of the "best" or most efficient level of effort for project development. These measurements may also be used to derive the probability of success for a given level of effort. Retaining the full set of estimates and revisions made for each project should also increase the accuracy of estimates.

It has also been suggested here that the estimates and data be retained for unsuccessful projects. Learning from previous mistakes or unprofitable approaches is also valuable. It can eliminate unnecessary duplication of effort, identify past errors in technological efforts, and uncover planning oversights and invalid assumptions.

Post-Operational Evaluation.

The introductory quotation of this chapter is applicable not only to the R&D projects but to the estimating and planning methodology used to develop the projects as well. The examination of yesterday's plans and today's results can yield great improvement in today's plans and tomorrow's results. Many volumes have been devoted to R&D efforts and the gross estimates that are so common, but there has been dangerously little analysis of the reasons for errors. The analysis has been hindered by undocumented and undated changes in project characteristics. Whether this analysis has simply not been undertaken, or has been tried unsuccessfully, or has been completed successfully and the results withheld, has not been determined. The analysis is difficult to perform, and may require a considerable delay, but it is nonetheless indispensable. Post-operational evaluation of the planning and estimating techniques, technological and administrative methods, and promulgation of the results, are vital. Without them, the elements of mythography will continue to multiply, the estimates will continue to be inaccurate, and time-consuming project changes will continue to disrupt the R&D program.

A distinction is made here between test and evaluation of the end products, which is being conducted in some detail, and the evaluation of the data used for estimates, the procedures and relationships used to derive the relationships, and the techniques employed in analysis from scenario to project selection to project completion. The gap may

be partially closed by increasing communications between OEG and similar groups and the rest of the R&D community, but the scope of the evaluation must also be extended.

Data are not collected for the sole purpose of filling out the data bank. It is collected to determine what kind of errors occurred, where they occurred, why they occurred, and how to prevent their recurrence. It should also be used to identify exceptional success in predictions and development, and the reasons therefor. There are obvious deficiencies in current estimating techniques. A critical analysis of planning and estimating techniques--an analysis based on study of the operational result of the project--is the only effective means of improving the process. A simple increase in the amount of data may never by itself achieve the desired results. No project should be considered complete until this type of analysis has been performed.

For in-house projects, it is a relatively simple matter to state the requirement for post-operational analysis of each activity's efforts by that activity, and await the results. For work done for the Navy by universities or industry, the contract should require review of the operational results of the project to analyze the planning and estimating efforts that went into the project. The importance of requiring a critical final evaluation by the personnel who performed the work cannot be overemphasized; they are the only ones who know exactly what went on and why. The benefits continue. The analysis also provides information for use in contractor selection. (The frankness and validity

of the final analysis can be considered as well as the degree of success attained in the project.) And the contractors can use the analysis to make improvements in their future efforts--improvements which they might not otherwise attempt and improvements which they might not otherwise recognize for lack of information on the final results of their efforts.

Two procedures suggested earlier can make substantial contributions to the post-operational analysis. The multi-purpose R&D reporting form calls for the initial estimates, the date and reason for each and every revision to each and every project characteristic, and the final characteristics of the operational product. This records the entire sequence of estimates and will help locate errors. The recommended list of assumptions made in performing the study and development provides an excellent starting point in determining the reasons for the errors.

Evaluation of the completed product will provide information on when simplifying assumptions can be made without introducing gross errors. It may also be possible to identify areas where the assumptions introduce consistent and predictable errors, and this can be equally valuable.

At the beginning of a project or study, the awareness of the final analysis requirement may reduce the acceptance of doubtful premises in the approach.[139] It is difficult to measure the value of a healthy

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[139] B-47, pp 15.

attitude of constructive criticism, but the value is there and it may even surpass the more obvious benefits.

If the source of the data used is well documented in the report, it may be possible to identify inaccuracies or inconsistencies in a particular data source, or information on the validity of extrapolations performed, or a poor comparison between projects assumed to be similar.[140] The information obtained from the post-operational analysis of the project can be used to promptly up-date the data and estimating relationships used.

Additional insight into the validity of the model can be obtained by applying the model to the finished product characteristics and comparing the model results with the actual. The analytical procedures used in prediction are not restricted to a single application,[141] but attain the most useful results when applied on a continuing basis. The relatively simple process of making an additional computer run can check out the final results and the accuracy of the model. The comparison can isolate the error and eliminate it, or at least reduce it, and improve future models and techniques.

A more difficult problem that can be addressed in the final evaluation is the determination of the cause of improved estimates. Did improvements come because the data bank was expanded and the predictions became more accurate, or did the activity improve its analytical

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[140] B-30, pp 2-130.

[141] A-1, pp 8.

techniques?[142] Again, the reporting techniques suggested can make this task somewhat easier.

It would be quite easy and appropriate to continue the discussion of the post-operational analysis of R&D projects for at least a dozen pages, but the point has been established. The after-the-fact evaluation of R&D effort has not even scratched the surface of the wealth of knowledge available, and further delay in its implementation would be a gross dis-service to the entire program.

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[142] A-17, pp 114.

## Chapter 9. Summary and Program Consistency

"Chief Executive's Utterly Exact Method for Measuring Scientific Research:

I multiply your projects by the words I can't pronounce,
And weigh your published papers to the nearest half ounce;
I add a healthy bonus for research that's really pure
(And if it's also useful, your job will be secure).
I integrate your patent rate upon a monthly basis
And I fugure what your plan in the race to conquer space is;
Your scientific stature I weigh upon some scales
Whose final calibration is the company's net-to-sales.
And so I create numbers where there were none before;
And thus have facts and figures and formulas galore --
And the volume of statistics make the whole thing very clear:
Our research should cost exactly what we've budgeted this year!

Ned Laudon
General Electric[143]

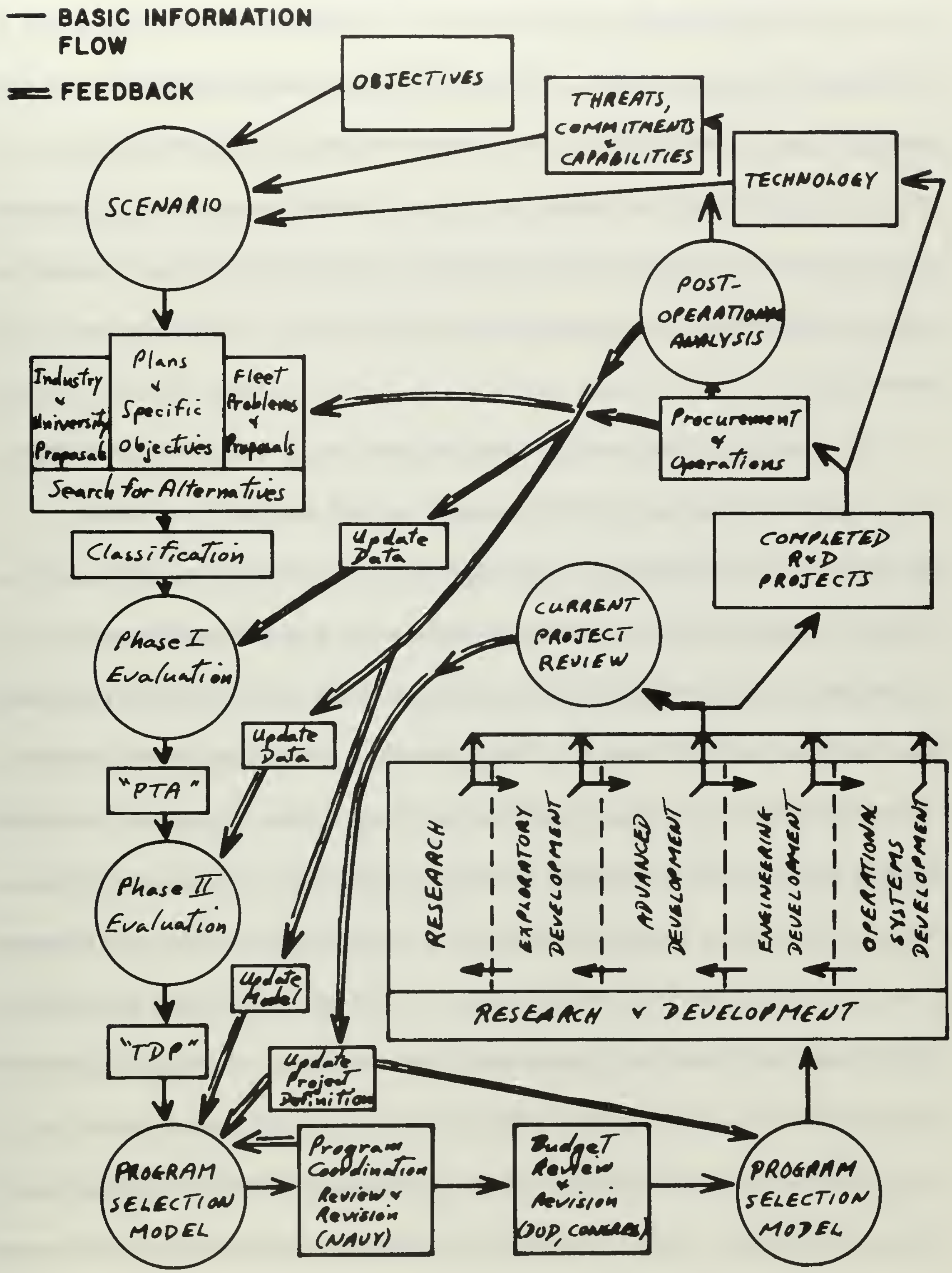
The preceding chapters have also generated numbers where there were none before, but a stronger case has been presented for them than can be made for the procedure outlined above. The numbers required here are the $E_i$ and $E_{i_o}$ -- the military values of proposed and existing capabilities. The information represented by these numbers is used extensively throughout the R&D process. Figure 9-1 is a schematic summary of the R&D process.

RDT&E in the Navy is a very large and complex process. The organization must deal with a tremendous variety of research and development projects. The DoD Planning-Programming-Budgeting process has had considerable influence on the structure of the

[143] B-50, pp 78.

FIG. 9-1

SCHEMATIC SUMMARY OF R&D PROCESS



organization. The trend appears to be toward conducting business in terms of developing the scenario, formulating plans and policies, converting the plans and policies, to the program and budget, and executing and appraising the program. The functional activities are coordinated at each phase. The programming and budgeting phase is incorporated in the FYDP; it was observed that the FYDP includes only those R&D projects which have been formally approved. Chapter 1 summarized important R&D elements in the organization, the planning documents, project development procedures, and reporting documents.

The research and development process must deal with the future -- an uncertain future. The international and domestic political situation is ever-changing. The objectives of the nation, DoD, and the Navy change with the political situation and the advancement of technology. The alternatives available to meet these objectives must be sought out and evaluated. The evaluation must predict the characteristics of the end product and the cost resources, and time required to produce it. The successful output of the process is intentionally designed to change the future that must be predicted. This uncertainty greatly complicates the R&D manager's task of controlling the widespread and decentralized organization's activities. Chapter 2 discusses some of the organizational techniques which have been employed to cope with this problem, and the communications problems which have arisen. Chapters 1 and 2 describe the nature of the problem addressed.

There are three characteristics of the research and development process which overshadow all others. Two have already been mentioned: complexity and uncertainty. The third is the dynamic nature of the process. There are no static decision points. There is no one point in time where projects submit themselves for an orderly review and one-shot program formulation, although the annual Congressional budget review requires both. An effective R&D program can be attained only if the review and program formulation are constantly being updated. The order of topic presentation was based on the life cycle of an individual project. Each of the phases discussed is conducted on a year-'round basis with a sequence of projects.

Chapter 3 discusses project genesis. The current environment and anticipated changes to it are expressed in a scenario. The inputs to the scenario are the general objectives of the nation, DoD, and Navy; predicted and current threats, commitments, and capabilities; and anticipated advances in technology. In addition to the political and military considerations, the scenario addresses the availability of manpower and other resources. A year-by-year breakdown of expected events is the most useful form for the presentation, even if the time estimates must be crude.

The scenario is used to formulate plans and more specific objectives. The planning documents were described in detail in Chapter 1. They attempt to outline force levels and capabilities well into the future. It is desirable to include indications of the relative importance

of these capabilities. The NRO, EDG, and GOR/TSOR are developed from the planning documents. Quantification of the subjective relative importance of the capabilities is most useful at this point. These documents in turn give rise to project proposals.

Under the present conditions, most R&D proposals originate within the R&D community in response to these documents. While the present number of projects is sufficient to keep the R&D activities busy, it is suggested that the search for alternative proposals be expanded. Some proposals are received from industry and the universities, and their proposal input could be increased by providing a list of topics in which the Navy has a particular current interest. A direct input from the fleet could greatly increase the sensitivity of the Navy's research and development to existing problems. It is simply not reasonable to expect the top levels of the Navy organization to be familiar with all operating problems being experienced by three-quarters of a million men; it would be a physical impossibility even if the top management had nothing else to do.

One source of fleet information is the increasing number of officers with post-graduate training. The Navy makes a substantial investment in their training and cannot afford to overlook any possible return on that investment. But the P-coded officers are not the only potential source of proposals. The efforts of OEG and similar operations research activities are invaluable inputs. An informal "beneficial R&D suggestion" program could increase fleet-wide awareness of a responsibility to seek improvements. This program would increase the relevance

of the R&D effort, take better advantage of the Navy's training, provide increased personal satisfaction for all participants, and increase the chances of obtaining the best proposals.

The magnified search for alternatives should include a thorough review of topic literature. Much effort can be conserved by determining what has already been done to solve particular problems. The literature search has itself become an unreasonably difficult problem. The volume of printed matter is so great that a thorough search is prohibitive without automated services similar to those provided by DDC but on a much broader basis.

The more extensive search for problems and alternative solutions requires classification to direct the information to the proper activities. It is suggested that a centralized clearinghouse be designated for this purpose. The clearinghouse would also assist existing procedures. It would determine the activity best suited to address the proposals, group related problems and proposals, and identify other project interrelationships to help establish early communications and coordination.

Concurrently with the classification, a very rough evaluation is performed to identify proposals which have been proven to be unsatisfactory, or are unsafe, or would create more problems than they could solve. The technological feasibility does not require detailed engineering evaluation at this point, but merely a determination of the proper R&D category.

The evaluation of proposals or projects begins with the idea and does not cease until the end result has been phased out of the system.

The classification process provides an initial screening for desirability. Chapter 4 considers two successive phases of evaluation, the first of which is required to produce the PTA, and the second, the TDP. Extensive review at higher levels is currently required for both phases.

It is suggested that the review, justified by recurrent difficulties in formulating the R&D program, may be substantially reduced. The first requirement for the reduction is the promulgation of weighted objectives. The second is the acceptance of fact that the information desired for a decision on project selection is not available in the desired accuracy or detail. These preliminary decisions can be made more efficiently by the activity managers, provided they have reasonable information on the relative importance of objectives. The reduction of review can cut lead times by decreasing the time required for decisions and the volume of communications.

The following information about proposed projects must be evaluated:

(1) characteristics and military value of outputs
(2) probability of successfully attaining the objective
(3) costs required to introduce the output into service
(4) time required to make the product operational
(5) personnel and facilities required to complete R&D
(6) reliability of desired product
(7) trade offs between cost, reliability, and time

Much of this information is not obtainable on proposals as they first enter the system, and the initial estimates are generally inaccurate.

The phase I evaluation is envisioned as a rapid but thoughtful preliminary investigation of the value and feasibility of proposals. It

is suggested that rather than attempt to overcome the uncertainty with detailed evaluation at this point, the managers should merely accept the uncertainty and develop empirical estimating relationships to compensate for it. Proposed interrelationships continue to develop, and the supporting communications and cooperation are established. The magnitude of effort should be measured in man-hours, rather than man-years. Problems in development can be predicted, and support at more fundamental levels can be requested. An early start of actual development can be made in these problem areas. The phase I evaluation requires flexibility of personnel assignment and a set of basic estimating relationships at each activity. The possibility of transferring personnel from completed projects to phase I evaluation and literature review should be considered.

The phase II evaluation is considerably more detailed, but it must also accept the unavailability of all desired information. Alternate solutions are defined and displayed on PERT diagrams. Estimates become more accurate; personnel and facilities requirements for R&D and initial estimates of production, operation and maintenance requirements can be made. All of the initial estimates suggested in the multi-purpose reporting form (Figure 7-1) should be supplied. Additional information on military values is required to make trade-off decisions. The procedures used for reliability estimations provide a good model for other estimating techniques, but the attempt to acquire more accurate information than is available must again be avoided.

One aspect of the evaluation is whether or not the work should be performed in-house. If the Navy has the capability, the work is generally done in-house. Contractors and consultants may be used to smooth the work load. If the personnel and facilities are not available, it may be desirable to acquire them in the presence of a continuing need and the absence of experienced contractors. In each activity, a knowledge of the capability of other Navy activities is required to take full advantage of in-house capabilities.

Current procedures for contractor selection are difficult to apply. The attempt to quantify subjective appraisals of military worth of existing and planned capabilities can provide a basis for measurement of previous contracting performance. The retention of successive estimates of the multi-purpose project reporting form will help in this evaluation, and the post-operational evaluation will indicate what the contractors and activities have learned from previous attempts.

The Contract Formulation/Contract Definition procedures again attempt to acquire levels of accuracy and detail that are unobtainable. This results in delays in reaching agreements and making decisions. Mutual respect and cooperation are essential to project success. They are difficult to write into a contract, but the contracting procedures must be flexible enough to permit sequential decisions. Realistic use of trade offs is being encouraged and should prove very helpful. Some authors have recommended that the contractors be allowed to make the trade-off decisions, but it is felt that this is an infeasible

and irresponsible move that the military cannot make. The contractors should be encouraged to consider and recommend trade offs, but the decision must remain with the men who will use the end products. Procedures for sharing both the risks and benefits of the R&D efforts must be developed.

Parallel development is encouraged and facilitated by the expanded search for alternatives, the classification process, and the evaluation process. An objective evaluation should be made of all manners of achieving desired goals, down-graded objectives, and interim solutions. The primary considerations in the decision for parallel development are the military value of the project, including the magnitude of improvement over existing capabilities; the degree of uncertainty in achieving success by alternative paths; the costs of alternative paths; and the qualitative differences (technological independence) of alternative paths. It is essential that these quantities be evaluated and that the existence of parallel paths be known and controlled.

There are numerous differences in the information and estimates for the five research and development categories. Measuring the potential contribution of research projects to development projects and increasing the input of fleet information to the research activities may lead to better means of allocating funds to the research category and to projects within that category. Similar measurements may prove helpful in the Exploratory Development Program.

Increased use of Advanced Development projects can be effective if it can avoid some of the administrative restrictions placed on Engineering and Operational Systems Development projects. If coordination of project or system component can be achieved without detailed and formal management, the component research may progress more rapidly.

The processes discussed above are most directly applicable to the Engineering and Operational Systems Development projects, although the latter projects are much more complex. The systems development projects usually receive the full treatment, starting with development of a particular scenario and ending with a voluminous report. Computer models and optimization techniques are usually employed in the evaluation. There is an unfortunate tendency to view this analysis as a one-shot process, rather than as a working tool for updating and revising the development plan and evaluating trade-off decisions. The great length of the reports degrades their communications effectiveness. The failure to list and evaluate assumptions is very critical. The uncertainties which must be treated in the report make the inclusion of dissenting opinions valuable aids to evaluation.

The dynamic nature of the R&D process makes it difficult to apply most standard optimization techniques to project selection. The model developed in Chapter 5 attempts to convert present subjective procedures into quantified, computerized selection to make the manager's job less difficult. The model and its inputs are summarized in Figures 5-3

and 5-4. The objective function incorporates the primary characteristics estimated in the evaluation process:

$$\text{Maximize } E^{***} = \sum_i \left[ \ell n(1 + T_i) \right]^{-1} K \cdot E_i(E_i - E_{i_o}) - C_i(IOC_i - IOC_{i_o}) \, x_i$$

$$+ \sum_i \sum_k d_{ik} \, x_i \, x_k$$

$$= \sum_i f \text{ (project duration)} \Big[ g\text{(project effectiveness)}$$

$$- h\text{(project cost)} \Big] \, x_i$$

$$+ \sum_i \sum_k \ell\text{(incremental effectiveness of combinations}$$

$$\text{of projects)} \, x_i \, x_k$$

The project effectiveness is measured by the expected military potential, and, by the difference between the expected potential and the value of the current capability. This term includes the probability of project success. Both terms are used to allocate effort in proportion to the category importance and the magnitude of the advance in effectiveness. The quadratic expression $\ell(\cdot)$ adds the increases of effectiveness resulting from combinations of included projects. Both $g(\cdot)$ and $\ell(\cdot)$ may contain the probability of success.

The cost function $h(\cdot)$ measures the cost of acquiring the new capability and the difference between new investment and operations, and replacement and continued operation of the existing capability. The latter permits acceptance of cost reduction projects. End item reliability is used to increase the cost of achieving the desired effectiveness. The time function $f(\cdot)$ includes the benefits of obtaining results

quickly, but degrades the importance of timing considerations relative to the other factors.

The problem is constrained by the availability of R&D funds, personnel, and facilities. The other constraints are used to control project interrelationships. A modification of the program is provided to permit parallel development. The input "projects" are defined to include alternative technological paths and effort levels.

Concepts of balancing the R&D program are difficult to define and apply. The objective function is designed to reduce the bias toward short-range, quick-return projects. Balance must be reviewed subjectively after the recommended program is generated by the model. Continuity of the program is also important; frequent stops and starts disrupt the R&D program. The continuity considerations require that project definitions be frequently updated with new estimates of cost, time, probability of success, etc. It is possible to add an artificial bias to projects which are already underway to increase continuity, or the model can be used to select only such projects from the inactive list as may be undertaken by the reduced number of personnel facilities, and funds available, given that no current projects are to be dropped.

The programming of the model is difficult. A ready-made solution has not been found, but there are several approaches which indicate that the solution is obtainable. As an interim measure, the following procedure is suggested:

(1) Compute the value of the objective function for each potential project. (A cut-off point may be established below which projects will not be considered in the selection model.)

(2) Order the projects by decreasing value.
(3) List separately the potential incremental values for pairs of projects.
(4) Define a set of alternative programs which satisfy the personnel, facility, and R&D funding constraints. (The projects with highest value may be included until the constraints are approached, as a general rule of thumb.)
(5) Compute the full value of the objective function for each program defined.
(6) Review the results for potential areas of improvement; redefine programs and recompute as desired.
(7) Select the program with the highest value of the objective function.

This is an unsophisticated, brute-force approach, but it can generate many useful results while the optimization techniques are being developed.

Chapter 5 discusses a number of optimization techniques which have been suggested for use in the R&D process. Briefly, these techniques are the industrial dynamics approach, a set of differential equations representing the rates at which knowledge is acquired and applied, a linear programming selection process for research, some subjective and quantitative selection "rules of thumb," an accounting model, and a chance-constrained R&D funding program.

Chapters 6 and 7 address the problem of controlling research and development in progress. The model is used specifically for project selection, and since the selection process is going on more or less continually, the model is a control device. It requires a great deal of input information, and its output represents a similarly large volume of information in highly condensed form. It is suggested that the PERT diagrams required in the TDP's be displayed together to provide model inputs and display outputs.

The individual PERT diagrams can easily be modified to show the use of personnel and facilities. By combining this information from each project, the input for two of the model's constraints can be determined. Samples of these displays are presented in Figures 6-1 and 6-2. A considerable effort may be required to extract the essential information from the TDP. A suggested modification -- and condensation -- of the TDP is developed in Figure 7-1. This modification calls for only 16 pages, with much of each page left blank in the early stages to permit convenient retention of early estimates and addition of new information and revised estimates. It is recognized that additional pages may be necessary in some cases, but the goal is reasonable and desirable. The form is to be used as a working document and for updating the activity manager's master plan. As significant changes occur, they are indicated on the form, forwarded to the activity manager, and transferred to the multi-PERT presentation. The same report can be used to update the project definitions, and another iteration may be performed with the model. This procedure is recommended for use even with relatively small projects. It shows the manager what has been done, what remains to be done, and which activities require special attention.

The use of PERT diagrams to show the relationships between projects is standard procedure. Some newer developments include arc-transition probabilities in addition to the conventional PERT information. The potentials of PERT are still being extended, and further study --

including graph theory applications -- may develop additional project selection techniques.

The control process requires standardization in many areas. The modified TDP form suggested in Chapter 7 can be used for control, reporting to higher management levels, and data analysis. This certainly contributes to standardization. The use of standardized estimating procedures was mentioned earlier. The amount of documentation and explanation required could be substantially reduced from the current needs, but the engineering estimates applied to the statistical estimating relations must still be indicated on the report. Standardization of evaluating and reporting procedures facilitates and simplifies the transfer of information.

A reduction in the amount of top level review for control is a possibility which deserves detailed examination. Lead times can be significantly reduced by speeding the decision process. If the activity managers and project managers are supplied with a current evaluation of objectives, they are in the best position to make the selection and control decisions. If they are permitted to make the decisions and proceed with work, the work can progress more rapidly and the higher levels of the organization can return to "management by exception." Top management thus gains more time for critical decisions when the desired information is fully available. The volume of reports is reduced to simplify review and accelerate decision-making.

The transition between projects can be smoothed by permitting decisions at the activity level. The need to convey the many changes in an R&D program through the chain of command can easily introduce

unnecessary delay in proceeding with new projects. The policy of assigning personnel to literature review and phase I evaluation enables the manager to have the next project team ready to go to work as soon as facilities become available.

The efficient combination of accounting, budget planning, and military planning on a year-'round basis yields high dividends in program continuity and control. A flexible personnel assignment policy is mandatory in coping with the uncertainty of the R&D process and in improving communications. Bringing researchers into the planning process in phase I and in subsequent evaluation and updating of the multi-purpose reporting form can increase the researchers' appreciation of the managers' problems and their personal satisfaction.

The importance of accurate and timely communications has been apparent throughout. The complexity of the organization, the magnitude of uncertainty and frequent revisions of estimates, and the dynamic nature of the R&D process make efficient communications absolutely necessary. The classification and evaluation processes are designed to improve communications, as is the multi-purpose reporting form. Formal but concise documentation of information transfer has been stressed throughout.

A centralized coordinating point is desirable to remove the bookkeeping functions of the review process from the offices of the CNR, CND, and DCNO(D).

The development of a substantial data base is one of the established goals of the research and development process. Unfortunately there has been a great deal of wasted effort in this area. Many previous reports contain inconsistent or unexplained data and estimates. Statisticians can physically combine data on the basis of the project title, but they cannot be held responsible for an interpretation of the results if the quantities being estimated are not accurately and consistently defined.

Critical values have been hard to identify and more difficult to measure. This has caused them to be omitted altogether in many instances. Without an attempt to evaluate the critical values in operational systems, the estimating procedures cannot improve.

Decisions which are left undocumented are most unlikely to yield to an evaluation of reasons for either marked success or failure. The omission of data on unsuccessful projects will greatly restrict evaluation of failures.

Even with thorough documentation and an extensive data bank, statistical estimates are strained by the usual requirement for extrapolation. The extensive use of engineering estimates as a means of refining the statistical estimates is highly recommended. It is also necessary to determine which characteristics are identifiable in the initial planning stages to provide a basis for empirical approximations.

There are logical reasons to provide a centralized automated data processing capability, and equally logical reasons for maintaining such a capability at each activity where the data can be most easily updated

and where it is most frequently used for estimating. The tremendous volume of information which is ultimately desired points toward future decentralization of ADP. Whether the data is centrally located or not is secondary to the promulgation of information on the types of data which are available.

The procedures proposed herein require new data on the military values of projects and probability of success. Both may contribute to a means of measuring the return on research and development efforts, which in turn can improve the allocation of effort and funds among projects, among categories, and to Program 6 among the DoD programs.

The inadequate post-operational analysis is the most serious deficiency in the entire R&D process. Measured against existing capabilities in R&D management, it is the only serious deficiency. Failure to exploit post-operational analysis of projects is inexplicable and deplorable. The post-operational analysis is an indispensable means of providing feedback to estimating procedures, data banks, model formulation, and the R&D community in general. Activities and contractors performing R&D projects should be formally required to complete a thorough analysis of their technological and managerial techniques used in each project, and to report the results. The multi-purpose report form and the specific listing of assumptions are both essential to the post-operational analysis.

This concludes the summary. The preceding chapters provide amplifying information and description of reasons supporting the techniques and procedures listed briefly in this chapter.

Chapter 10. Conclusions.

> Thus, trying to look into the future intelligently is the thing which causes every research administrator to lose sleep. This is when the wisdom to make proper choice, patience to await results, and strength to justify expenditures become so important.[144]

The complex, uncertain, and dynamic nature of the research and development process pose extremely difficult problems for the manager. There are no easy solutions; the characteristics quoted above can only continue to grow in importance. The purpose of this analysis was to find and develop procedures to assist the manager in making decisions. The conclusions are listed below.

1. The Navy has well-defined procedures for R&D management. The procedures compare favorably with generally accepted management policies.

2. The search for alternative projects should be expanded. Fleet problems and proposals should be solicited directly. This would increase the relevance of R&D projects and permit greater utilization of the Navy's officer and enlisted training program.

3. A thorough search of topic literature is necessary, but it is nearly impossible at present. Bibliographic services are required similar to those presented by DDC but on a broader basis.

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[144] B-42, pp. 53.

4. A centralized clearinghouse or coordinating point is proposed to serve the following functions:

(a) classify incoming proposals
(b) establish early communications and cooperation on interrelated projects, and provide control of parallel development
(c) combine activity listings of the type of data available, for general promulgation
(d) perform bookkeeping integration of activity research and development programs for CNO, ASN (R&D), SECNAV, and other offices.

5. The sequential availability and accuracy of estimates and information require closer attention.

(a) The evaluation process attempts to acquire greater estimating accuracy than is available at any given step.
(b) Extensive delays occur in CF/CD phase because of contractor-government disagreement on details; more flexibile contracting procedures are required to permit sequential decisions.
(c) Excessive review before information is available for decisions results in further delays; phase I review should be expedited at work level and removed from top-level control.

6. A small percentage of scientists and engineers should be assigned to phase I evaluation and literature review on a rotating basis at each activity.

7. Control and use of parallel development are facilitated by the expanded search for alternatives, the classification process, and the evaluation process.

8. Optimization models developed for systems development projects should be used throughout project development to evaluate trade offs and identify deviations from expected results.

9. The model developed in Chapter 5 approximates current subjective selection techniques and is useful in both long-range planning and interim reallocations.

10. The multi-PERT display complements the model in all phases of selection and control.

11. The multi-purpose reporting form should be used for evaluation, control, and reporting. Its advantages are:

(a) concise presentation of critical information
(b) improved continuity through all phases of project life
(c) convenient presentation of project history for review, data compilation, and post-operational analysis
(d) reduction in number of reports required.

12. There is a tendency for decision levels to rise. They should be forced downward as close to the working level as possible.

13. The development of the data bank continues to be critical. Documented reporting is essential. Specific investigation is required of:

(a) accuracy of estimates as a function of project life time
(b) empirical relationships to compensate for error trends
(c) engineering estimates of differences between proposed project and the established average
(d) critical values identifiable early in project life cycle
(e) unsuccessful projects
(f) new data on military value of projects as a means of measuring the returns on R&D effort.

14. The attempt to quantify the military potential of proposals is necessary.

(a) A measure of R&D output is required to replace such unfortunate measures as the volume of published material.
(b) Knowledge of the value of objectives and projects is essential to the formulation of an effective R&D program.
(c) Knowledge of the value of objectives and projects is essential to lowering the decision level to permit management by exception.

15. Rapid, accurate, and documented communications are essential to the entire R&D process.

16. Inadequate post-operational analysis of the planning, evaluating, modeling, and technological methodology is the most serious deficiency in current practices.

(a) Post-operational analysis is the only means of establishing adequate evaluation, feedback, and correction of management techniques.
(b) Post-operational analysis should be a formal requirement for all Navy activities and contractors.

17. The following additional areas are identified for further study.

(a) information flow rates in Navy R&D activities
(b) probabilistic modifications to PERT, including ARMNET, Modern MISER, and graph theory
(c) optimal solution of model formulated in Chapter 5.

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# APPENDIX A

## RDT&E PROGRAM FUNDING[145]
(Millions of Dollars)

| | Research | Exploratory Development | Advanced Development | Engineering and Operational Systems Dev. | Management and Support |
|---|---|---|---|---|---|
| Air Force | | | | | |
| 1964 | 84.5 | 305.0 | 396.5 | 2184.7 | 654.6 |
| 1965 | 93.4 | 318.4 | 310.4 | 1845.8 | 637.9 |
| 1966 | 102.9 | 315.9 | 478.7 | 1610.5 | 668.7 |
| Army | | | | | |
| 1964 | 81.5 | 243.0 | 80.2 | 847.5 | 170.4 |
| 1965 | 91.4 | 237.7 | 111.1 | 714.7 | 221.4 |
| 1966 | 91.8 | 253.6 | 125.6 | 752.7 | 240.6 |
| Navy | | | | | |
| 1964 | 136.3 | 343.6 | 134.6 | 577.9 | 206.0 |
| 1965 | 124.5 | 338.3 | 150.6 | 566.5 | 185.8 |
| 1966 | 137.6 | 342.1 | 150.6 | 615.1 | 154.9 |
| ARPA | | | | | |
| 1964 | 46.0* | 225.0* | | | |
| 1965 | 44.7 | 227.3 | | | |
| 1966 | 47.0 | 230.0 | | | |

*1964 ARPA Research shown as 17% of total ARPA Budget (1965 is 16.4%, 1966 is 17%) since breakdown is not given in hearings.

145 B-25, pp 21-21A.

APPENDIX A (continued)

RDT&E PROGRAM FUNDING (continued)
(Millions of Dollars)

| | Research | Exploratory Development | Advanced Development | Engineering and Operational Systems Dev. | Management and Support |
|---|---|---|---|---|---|
| TOTAL | | | | | |
| 1964 | 348.3 | 1116.6 | 611.3 | 3610.1 | 1031.0 |
| 1965 | 354.0 | 1121.7 | 572.1 | 3127.0 | 1045.1 |
| 1966 | 379.3 | 1141.6 | 754.9 | 2978.3 | 1064.2 |
| Activity as Proportion of Total | | | | | |
| 1964 | 5.2 | 16.7 | 9.1 | 53.8 | 15.4 |
| 1965 | 5.7 | 18.0 | 9.2 | 50.4 | 16.8 |
| 1966 | 6.0 | 18.1 | 12.0 | 47.1 | 16.8 |

SOURCE: 1965 and 1966 Hearings before a subcommittee of the Committee on Appropriations, House of Representatives on Department of Defense Appropriations, Government Printing Office 1964 and 1965.

Note: 1964 and 1965 figures are those presented in 1965 and 1966 hearing respectively. 1966 figure is the budget request shown in 1966 hearings.

## APPENDIX B

### DoD Programs[146]

I Strategic Forces--combines former categories of strategic retaliatory forces and continental air missile defense forces (FBM force)

II General Purpose Forces--relied upon for combat operations short of general nuclear war (Navy units other than FBM force)

III Specialized Activities--includes intelligence and security, national military command system, communications, and other activities

IV Airlift/Sealift Forces--provide airlift and sealift for troops and cargo (MSTS)

V Guard & Reserve Forces--equipment, training, and administration of Reserve and National Guard forces

VI Research & Development--all R&D prior to decision to produce for inventory

VII Logistics--wholesale supply and maintenance activities

VIII Personnel Support--includes most training activities, major medical activities; absorbed retired pay category

IX Administrative--general overhead costs

Military Assistance--separate program, but computer will accept only 9 program numbers

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[146] B-17, pp 34-35; A- 13 , pp 92-93.

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13. ABSTRACT

Many management techniques have been discussed for application to various segments of the research and development process. All segments are analyzed to identify common problems and develop a consistent set of techniques to facilitate Navy program management. A selection model, program display, revised reporting techniques, and post-operational analysis are among the major topics discussed.

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| Project Selection | | | | | | |
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